

2

GENERAL SURVEY

2.1 TERMINOLOGY AND SCOPE

*The great book of Nature lies ever open before our eyes and the true philosophy is written in it... But we cannot read it unless we have first learned the language and the characters in which it is written... It is written in mathematical language and the characters are triangles, circles and other geometric figures.*¹

Galileo GALILEI
Florence 1623

*In physics, experiments have a larger power to persuade than reasoning.*²

Blaise PASCAL
Paris 1663

PERCUSSION, concussion, collision, impact, explosion, implosion, detonation and shock waves are rapid mechanical phenomena that are related to each other. Since they cannot be resolved by the naked eye, for a long time their sudden and discontinuous nature was hidden behind a veil of vague hypotheses and suppositions. First experimental evidence on physical quantities such as motion (velocity, acceleration), force and thermodynamic state (density, pressure and temperature) were not obtained until significant progress was achieved in the late 19th century in high-speed diagnostics, visualization techniques and photographic recording. Increasing individual knowledge of high-speed events led observers to recognize connections between different phenomena, which stimulated analyses of interrelations. This initiated a purposeful, more systematic research characterized by experimental testing of qualitative hypotheses, which, beginning in the mid-1940s, eventually led to computer-supported quantitative modeling of new concepts.

Mechanics developed in the 17th century from mere contemplations of accounts of observations and experiences into one of the main pillars of the physical sciences. In the late 16th century, the Italian physicist and mathematician Galileo GALILEI reestablished mathematical rationalism over ARISTOTLE's logico-verbal approach and suggested that experimentation should be used primarily to check theoretical deductions, while the French philosopher Blaise PASCAL favored the principle of empiricism and proposed the experimental approach. Both conceptions, supplementing each other in a unique manner, established the principle that was to become the guiding maxim of modern science.

Max PLANCK,³ an eminent German physicist, appropriately said, "Theory and experiment, they belong together; the one without the other remains unfruitful. We are fully justified in applying KANT's well-known words on the unity of concept and intuition and saying: theories without experiments are empty, experiments without theory are blind. Therefore both – theory and experiment – call for proper respect with the same emphasis."

Mechanics became the most important and advanced branch of *natural philosophy* – a term used by Sir Isaac NEWTON to denote investigations of laws that hold in the material world and the deduction of results that are not directly observable, and which is today covered by the field of *physics*. According to the German philosopher Immanuel KANT, science is characterized by an ordered arrangement of gained knowledge, based on data and observed phenomena as well as on similar cases and their critical testing through the application of "creative inspiration." Phenomena that appeared similar were particularly puzzling to early naturalists, such as

- ▶ the instantaneous, discontinuous character of the velocities observed during the percussion of tangible bodies and of air molecules at a steep shock front;
- ▶ the wall-like, crested front of a tidal bore in a river and the steep front of a shock wave in air;
- ▶ the bow wave generated by a body moving through water (*Kelvin envelope* or *Kelvin wake*) and the head wave (*Mach cone*) generated by a projectile flying supersonically, or by a planet moving through the solar wind;
- ▶ the irregular reflection properties of hydraulic jumps and shock waves; and
- ▶ the propagation behavior of a shock wave and a detonation wave.

Since the first scientific investigations of the nature of percussion of tangible bodies, an increasing number of new discontinuous high-rate phenomena have been observed, calling for new definitions, explanations and classifications. To some extent the technical terms used by early natural philosophers to describe high-speed phenomena reflect their early knowledge and understanding. However, as we have looked more deeply at the physical processes over decades of increasing research activity, the meanings of some of the terms have changed, and our insights into their complexity

¹ G. GALILEI: *Il saggiaiore* ("The Assayer"). Mascardi, Roma (1623).

² "Dans la physique, les expériences ont bien plus de force pour persuader que les raisonnements." See B. PASCAL: *Traité de la pesanteur de la masse de l'air*. Desprez, Paris (1663), chap. I.

³ M. PLANCK: *Zum 25jährigen Jubiläum der von W. FRIEDRICH, P. KNIPPING and M. VON LAUE gemachten Entdeckung* [Lecture held during the meeting of the DPG in Berlin on 9th June 1937]. In: (hrsg. vom Verband dt. Physikalischer Gesellschaften) Max PLANCK. *Physikalische Abhandlungen und Vorträge*. Vieweg & Sohn, Braunschweig (1958), Bd. III, pp. 364-367.

has created a wealth of new, related terms. The main technical terms used in the fields of percussion, collision, impact, explosions, detonations and shock waves are discussed below in more detail.

2.1.1 PERCUSSION, CONCUSSION, IMPACT, AND COLLISION

Many early terms describing high-speed phenomena were derived from Latin, then the language used in most learned works: examples include the terms *collision*, *percussion*, *explosion*, and *detonation*, which are still in use today. However, reflecting the state of knowledge of each time period, they only gradually evolved into their present-day meanings. This slow process of arriving at clear definitions, starting in the 17th century, was not caused by poor communication. Surprisingly, many early naturalists used to exchange knowledge and ideas with their colleagues abroad at an intense level via correspondence or by traveling. Actually, in order to comprehensively characterize the essentials of high-speed phenomena it is necessary to obtain a deep understanding of how the phenomenon in question evolves over time, both qualitatively and quantitatively. This learning process, which only evolved slowly because of the insufficient temporal resolution of early diagnostics, will be discussed in more detail in Sect. 2.8.

Percussion. The term *percussion*⁴ designates the action of striking of one moving object against another with significant force. Since the birth of classical percussion in the 17th century {HUYGENS \Rightarrow 1668/1669; WREN, WALLIS \Rightarrow 1669; Sir NEWTON \Rightarrow 1687; \Rightarrow Fig. 2.16}, the term has been conventionally applied in reference to solid bodies, and in this sense it has also been used throughout the evolution of (terminal) ballistics. The fundamental theory of percussion was based on two spheres of the same material but different masses moving in a straight line and impacting either head-on (*central percussion*) or at an angle (*oblique percussion*).

Real percussion phenomena depend on the shapes of the impacting bodies, their masses, their elastic properties (rigid, perfectly elastic, elastic or inelastic), and their initial velocities. In purely elastic percussion no permanent deformation takes place, and both momentum and kinetic energy are conserved. In the early development of the kinetic theory of gases, percussion models generally assumed that the gas molecules collide with one another or with the wall perfectly

elastically, like hard elastic spheres (e.g., glass marbles, billiard balls). In contrast, inelastic percussion between moving bodies produces permanent deformation. While momentum is conserved here as well, kinetic energy is not. Very old examples of inelastic percussion are the soft-hammer percussion method used in flint knapping { \Rightarrow Fig. 4.2–D(d)} and the wooden mallet used in combination with a metal chisel in stone masonry { \Rightarrow Fig. 4.2–E} and wood carving. Modern vehicle design attempts to largely absorb the kinetic energy in the case of collision accidents by using materials which deform plastically.

The word *percussion* [Germ. *der Stoß*] – used almost exclusively by French and English natural philosophers throughout the 17th and 18th centuries, and also partly in the 19th century – relates to the analysis of the physical process involved when bodies striking each other with some degree of force, while the resulting effect is described by words such as shock, blow, impact, knock *etc.* Percussion refers to solid bodies, more rarely to liquids, and to air.⁵ It is interesting to note here that the word “percussion” will prompt most English-speakers to initially think of music rather than physics, ballistics and engineering. On the other hand, some encyclopedias (such as the 1974 edition of the *Encyclopedia Americana*) only refer to the medical meaning of the term *percussion* {VON AUENBRUGGER \Rightarrow 1754}.

In modern textbooks on mechanics, the classical theory of percussion is often referred to as the “theory of impact,” while in physics textbooks it is usually called the “theory of collision.” Indeed, Edward J. ROUTH { \Rightarrow 1860} used the term *impact* rather than *percussion* in his widely used textbook *Dynamics of a System of Rigid Bodies*. Thomas J. MCCORMACK, who translated Ernst MACH’s book *Die Mechanik in ihrer Entwicklung, historisch-kritisch dargestellt* {E. MACH \Rightarrow 1883} into English, followed ROUTH’s terminology and translated *Die Theorie des Stoßes* into “The Theory of Impact.” However, the term *center of percussion* – coined in England in the late 17th century {WALLIS \Rightarrow 1670/1671} – has long been used by both mechanical engineers and physicists.

The principle of percussion has been widely applied in military technology, but also in civil engineering and medical diagnostics which created a number of percussion-related terms (see Sect. 2.2.4).

Concussion. The term *concussion*⁶ describes the action of violently shaking or agitating, particularly in relation to the shock of impact. In the past it was also used to describe the

⁴ From Lat. *percūtēre*, meaning to strike or thrust through.

⁵ J.A. SIMPSON and E.S.C. WEINER: *The Oxford English dictionary*. Clarendon Press, Oxford (1989), vol. 11, p. 528.

⁶ From Lat. *concussio*, meaning a “shock” or “blow.”

sudden shaking actions of violent seismic waves,⁷ or in gunnery.⁸

Today the term *concussion* is primarily used in medicine to designate a period of paralysis of nervous function resulting from an injury to the brain which, produced by a violent blow to the head, causes temporal unconsciousness. Concussions of the brain can affect memory, judgment, reflexes, speech, balance and coordination. Many encyclopedias, particularly the older editions, refer to this meaning only. In modern geology, a *concussion fracture*⁹ designates one of a system of fractures in individual grains of a shock-metamorphosed rock that is apparently formed by violent grain-to-grain contacts in the initial stages of the passage of a shock wave.

The term *concussion* is also used in weapons technology such as the *concussion grenade* (an antipersonnel device which uses a brilliant flash and loud bang to render an enemy in its vicinity blind, deaf and immobile for a brief period of time) and the *concussion fuse* (a bomb fuse used in ordnance that is set off in the air by the explosion of a previous bomb).

Impact. The term *impact*,¹⁰ when used in mechanics, is a single forceful collision and designates the process of momentum transfer between two moving bodies by violent percussion. Impact occurs when two bodies come together with a normal component of relative velocity at an initial point of contact. An impact frequently results in a sudden drop of velocity accompanied by a decrease in dynamic energy. When the two bodies first make contact at a single point, deformation will take place at that point and will progressively spread until the two bodies eventually make contact over the maximum area. In science, the term *impact* was apparently first used by the British chemist Richard WATSON (1781) and the Irish naturalist John TYNDALL (1863) to denote collision effects on an atomic level.¹¹ In his hypothesis on the formation of the lunar surface by meteorite impact, the U.S. geologist Grove K. GILBERT {⇒1893} first used this term to characterize a typical lunar ring mountain (“impact crater”).

(i) *Impact mechanics* is concerned with the reaction forces that develop during a collision and the dynamic response of structures to these reaction forces {STRONGE ⇒2000}.

(ii) *Impact engineering* is a rather new branch of engineering which is concerned with the response of structures and bodies to dynamic loads arising from exposure to blast, collision (“crash tests”) or other impact events, and the use of numerical codes in examining impact problems {Int. J. Impact Engng. ⇒1983}. The term *impact engineering* was apparently coined in the early 1980s. The first conference on this subject was held in 1992 {Int. Symp. on Impact Engng. ⇒1992}.¹²

- ▶ The term *impulsive loading* describes high-velocity processes which, for example, occur when an explosive charge is detonated in intimate contact with a body {RINEHART & PEARSON ⇒1954} or when one body impacts against another at high velocity.
- ▶ *Structural impact* is concerned with the behavior of structures and components subjected to large dynamic loads produced by explosions, impacts, tornadoes, tsunamis etc.
- ▶ *Structural impact engineering*, which explores the responses and energy-absorbing properties (including damage and failure) of various structural systems, requires a profound knowledge of material characteristics in the dynamic range. This is of particular interest for the crashworthiness design of aircraft, automobiles, trains, ships and marine structures {BARÉNYI ⇒1951; JOHNSON ⇒1978; JONES ⇒1989}.
- ▶ *Impact welding* is a technique of joining dissimilar materials that cannot be joined by other means (such as aluminium alloys to steel). There are two principle methods of propelling one part into another to form a weld: first by fast burning explosives and second by electro-magnetic induction/repulsion.

Impact engineering now deals with a wide variety of impact situations: it attempts to define the forces that occur during an impact event and the techniques that can be used to absorb these forces; for example, it addresses special but very important problems such as testing and modeling the resistance of aircraft components and jet engines to being struck by birds.

(iii) *Impact physics* is a more recent branch of solid-state shock wave physics that treats the wide spectrum of impact phenomena experimentally and theoretically from the viewpoint of dynamic materials science and thermodynamics, and addresses action as well as reaction effects. Impact physics is mainly derived from terminal ballistics, which

⁷ J.A. SIMPSON and E.S.C. WEINER: *The Oxford English dictionary*. Clarendon Press, Oxford (1989), vol. II, p. 677. • For example, Don George JUAN and Don Antonio DE ULLOA, referring to the terrible earthquake that happened in 1772 in Quito, wrote in their book *A voyage to South America* [Davis & Reymers, London, 1760], “The terrible concussion was general all over the province of Quito...”

⁸ William GREENER wrote in his book *Gunnery in 1858*, a treatise on rifles, cannons and sporting arms [Smith & Elder, London, 1858], “The proper shape and form of cannon to resist concussion...”

⁹ J.A. JACKSON (ed.): *Glossary of geology*. Am. Geol. Inst., Alexandria, VA (1997), p. 133.

¹⁰ From Lat. *impactus*, the action of striking or pushing at or against.

¹¹ J.A. SIMPSON and E.S.C. WEINER: *The Oxford English dictionary*. Clarendon Press, Oxford (1989), vol. VII, p. 695.

¹² M. MACAULAY: *Introduction to impact engineering*. Chapman & Hall, London (1986, 1987).

investigates the various events that occur when a projectile hits a target. Although this field is centuries old, the theory of terminal ballistics is a relatively modern development; it was first developed in the 1960s to satisfy military needs such as improving armor on military vehicles. However, studies of impact and penetration phenomena in terminal ballistics have also been motivated by interests in subjects as diverse as meteorite craters on the Moon and planets, meteoroid protection of space vehicles, and solid state physics of materials at extremely high pressures.¹³

Almost 50 years ago, Robert GRAHAM,¹⁴ a Sandia shock physicist, worked out a 105-page bibliography on *Impact Physics* consisting of a rather complete collection of over 5,000 references and abstracts on the subjects of (1) plastic wave propagation in bounded solids; (2) behavior of metals under explosive conditions; (3) dynamic photoelasticity; (4) penetration phenomena; (5) behavior of material at high strain rates; (6) lateral impact; and (7) impact measurement devices. All these subjects are now as before relevant in modern impact physics. The first book on the physical behavior of impacting solids was published by Werner GOLDSMITH {⇒1960}.

In solid-state shock wave physics, the term *symmetric impact* relates to a laboratory method of generating planar shock waves by shooting a plate, the so-called “flyer plate” {MCQUEEN & MARSH ⇒1960}, with a velocity W against a stationary plate of the same material as the flyer plate. In this special case, a pair of shock waves moving out with $\pm U$ from the interface at particle velocities $\pm u = \pm \frac{1}{2}W$ are generated. The symmetric impact allows the generation of a “standard Hugoniot” from a chosen “standard material” such as 24ST aluminum (an alloy of 4.5% Cu, 0.6% Mn, and 1.5% Mg), which facilitates the determination of Hugoniot curves for any solid material {⇒Fig. 2.13}.

Some research laboratories are particularly dedicated to the physical aspects of impact. For example, the U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground, MD has an *Impact Physics Branch* which is associated with the Terminal Effects Division of the Weapons and Materials Research Directorate (WMRD); and the Ernst-Mach-Institut (EMI) at Freiburg, Germany has an *Impact Physics Division*. Various American universities have *Impact Physics Groups*, such as the University of Dayton Research Institute (UDRI) at Dayton, OH and the Institute for Advanced Technology

(IAT) of The University of Texas at Austin. Traditionally, physical aspects of high-velocity impact phenomena are reviewed and discussed at the Hypervelocity Impact Symposium {HVIS ⇒1986}.

(iv) *Hypervelocity impact physics* is an entirely new field of research which is derived from impact physics and was established in the mid-1950s. It should be noted here that *hypervelocity* is a term that is used in different branches of science to classify quite different velocity regimes:

- ▶ Hypervelocity impact physics deals with the impact of matter at extremely high velocities, resulting in extreme pressure and loading rates. In particular, it encompasses events where, in contrast to the impact of common ordnance, the impact-generated pressures are in excess of the projectile and target strength. For most metals, the lower limit for hypervelocity impact is on the order of (only) 3 km/s.¹⁵
- ▶ For aerodynamicists, hypervelocity wind tunnels are testing facilities operated at airflow velocities greater than $M > 12$ (> 4 km/s).
- ▶ In line with the discovery of shatter cones found in the Kentland quarry in Indiana {BUCHER ⇒1933; BOON & ALBRITTON ⇒1938; DIETZ ⇒1960; SHOEMAKER ET AL. ⇒1961}, geologists have defined the term *hypervelocity* as velocities greater than the speed with which sound travels through average rock (> 5 km/s).
- ▶ For astronomers and astrophysicists, the term *hypervelocity* covers a very wide range. Meteoroids entering the Earth's atmosphere have velocities of up to 40 km/s. The speeds of extraterrestrial hypervelocity phenomena can range from several hundreds of km/s (e.g., the solar wind) up to 2,000 km/s (e.g., coronal mass ejections), and even to well in excess of 30,000 km/s (e.g., shock waves emitted from hypernovae).
- ▶ Nuclear physicists use electromagnetic accelerators to accelerate light particles (such as electrons, proton or α -particles) to hypervelocities that are asymptotic to the speed of light.

A hypervelocity impact is accompanied by an *impact flash*. Measurements in several optical, infrared, ultraviolet and even X-ray wavelengths allow astrophysicists to draw conclusions about the kinetic energy of the impact event and possibly about the physical state and nature of the impacted surface {Comet SHOEMAKER-LEVY 9 ⇒1994; Deep Impact Mission ⇒1999; SMART-1 ⇒2003}. Impact-flash phenomenology has been known for many years, and

¹³ J.L. SUMMERS and B.P. DENARDO: *Terminal ballistics*. In: (T.N. CANNING, A. SEIFF, and C.S. JAMES, eds.) *Ballistic range technology*. AGARDograph No. 138 (1970), pp. 157-165.

¹⁴ R. GRAHAM: *Impact physics*. Sandia Rept. SCR-59 (Dec. 1958); <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA395534&Location=U2&doc=GetTRDoc.pdf>.

¹⁵ H. FAIR: *Hypervelocity then and now*. 1st High Velocity Impact Symposium (HVIS), [San Antonio, TX, 1986]. Publ. in Int. J. Impact Engng. **5**, 1-11 (1987).

is now also being considered for missile-defense applications, in particular, remote diagnostics for kill assessment and target typing.¹⁶

Hypervelocity impact physics mainly includes studies of the basic phenomenology of cratering, of the impacts of complex structures in space, and of properties of materials at very high pressures. In particular, it is devoted to investigating and assessing the threat of hypervelocity impacts between any spacecraft and man-made debris or naturally occurring meteoroids in the near-Earth space environment, known as “Near-Earth Objects” (NEOs) {Asteroid 2002 MN \Rightarrow 2002}, as well as protecting spacecraft though passive shielding techniques {WHIPPLE \Rightarrow 1947}. Hypervelocity impact physics has also gained increasing attention in other branches of science, for example in *astrogeology*, a new branch of geology created in the early 1960s and dedicated to the study of extraterrestrial solid objects {LESEVICH \Rightarrow 1877}.

(v) *Impact chemistry* is a more recent interdisciplinary branch of science which investigates the shock- and heat-induced chemistry of impacted matter (mostly gases and solids). Examples encompass

- ▶ detection of unique chemical “signatures” of meteorite impacts in sediment deposits;
- ▶ possible high-temperature- and shock-wave-induced production of large amounts of nitride oxide in the atmosphere (acid rain) and the stratosphere (ozone depletion);
- ▶ devolatilization (or pyrolysis) in serpentine [(Mg, Fe)₃Si₂O₅(OH)₄], Murchison meteorite, serpentine-iron, and serpentine-pyrrhotite mixtures and their possible role during planetary accretion;¹⁷
- ▶ interaction of Jupiter’s atmosphere with incandescent fireballs at high altitude produced by the collision of comet SHOEMAKER-LEVY 9 where they formed plumes that subsequently collapsed over large areas;
- ▶ element anomalies (such as iridium which occurs in meteorites in much greater concentrations than in rocks on Earth); and
- ▶ the fate of organic matter during planetary accretion.¹⁸

(vi) *Impact geology* is a branch of planetary geology which treats the complex stages of cratering mechanics (e.g., com-

pression, excavation, emplacement of ejecta, crater collapse), the nature of impact structures (e.g., rock fragmentation, shock metamorphism, astroblemes), environmental effects on crater formation, the morphology of impact basins, numerical 3-D modeling of large-scale asteroid impact events based on field-structural data, and investigates the role of impact processes in the evolution of the Earth and other planets.

- ▶ Geologic *impact structures* are generally circular and formed by hypervelocity impact of an interplanetary body (*impactor*) on a planetary surface (target). Craters formed by very oblique impacts may be elliptical.
- ▶ The impact produces an *impact plume*, a hot cloud of debris. Plume modeling has been proposed by planetary physicists to calculate synthetic plume views, atmospheric infall fluxes, and debris patterns raised by impacting fragments of comets.¹⁹
- ▶ Large impacts can cause an *impact metamorphism* of rocks or minerals due to the passage of a shock wave. Strong shock waves can form an *impact melt* due to shock melting of rocks in impact craters.
- ▶ *Impact erosion* can wear away large rock fragments due to the emission of a strong blast wave during impact. Impact erosion may also account for an early episode of atmosphere loss from Mars.²⁰

(vii) In fluid dynamics the term *impact* generally refers to the high-speed interaction of gaseous or liquid matter with a (mostly) solid boundary.

- ▶ The term *impact loading* was apparently first used by Richard COURANT and Kurt Otto FRIEDRICHS in their textbook *Supersonic Flow and Shock Waves* {COURANT & FRIEDRICHS \Rightarrow 1948} to describe the rapid loading of a structure by a blast wave {BLEAKNEY \Rightarrow 1952}.
- ▶ In high-speed aerodynamics, the *impact pressure* at any point of a fluid is defined as the net balance between the total pressure (or stagnation pressure, also known as the “Pitot pressure”) and the static pressure at the point where the impact pressure is to be found.²¹
- ▶ In underwater explosions near solid structures, the bubble collapse may be accompanied by the formation of a high-speed re-entrant liquid jet directed towards the structure. This phenomenon is known as “jet impact loading.”²²

¹⁶ R.J. LAWRENCE ET AL.: *Hypervelocity impact flash at 6, 11, and 25 km/s*. In: *14th APS Topical Conference on Shock Compression of Condensed Matter* [Baltimore, MD, July/Aug. 2005]. APS, College Park, MD (2006), pp. 1349-1352.

¹⁷ J.L. FAUST ET AL.: *Impact chemistry of serpentine-iron planetesimals*. 28th Annu. Lunar and Planetary Science Conf. [Houston, TX, March 1997]. Conf. Proc. CD-ROM (Jan. 1997), Abstract #1711.

¹⁸ T.N. TINGLE ET AL.: *The fate of organic matter during planetary accretion: preliminary studies of the organic chemistry of experimentally shocked Murchison meteorite*. Origins of Life and Evolution of Biospheres **21**, No. 5/6, 385-397 (Sept 1991).

¹⁹ J. HARRINGTON and D. DEMING: *Models of the Shoemaker-Levy 9 impacts*. Astrophys. J. **561**, Part 1, 455-467 (2001).

²⁰ H.J. MELOSH and A.M. VICKERY: *Impact erosion of the primordial atmosphere of Mars*. Nature **338**, 487-489 (April 6, 1989).

²¹ H.W. SIBERT: *High-speed aerodynamics*. Prentice-Hall, New York (1948), pp. 37-38.

²² G.L. CHAHINE and K.M. KALUMUCK: *The influence of structural deformation on water jet impact loading*. J. Fluids Struct. **12**, 103-121 (1998).

- ▶ The term *liquid impact* encompasses the dynamics of liquids. Since the 1960s, this has become an area of interdisciplinary research stretching far beyond classical fluid dynamics and materials research {LESSER & FIELD \Rightarrow 1983}.
- ▶ The high-velocity impact of liquid droplets against a solid metal surface, which causes serious damage due to erosion, has long been a problem for steam turbine designers and operators {THORNYCROFT & BAR-NABY \Rightarrow 1895; S.S. COOK \Rightarrow 1928; \Rightarrow Fig. 4.14–C}.
- ▶ With the advent of supersonic and even hypersonic flight velocities, the same phenomenon became of increasing concern in the aircraft and (later) in the aerospace industries due to the rain erosion problems sustained by aircraft {U.S. Air Force \Rightarrow 1945; The Royal Society \Rightarrow 1965}, missiles and reentry vehicles {HEY-MANN \Rightarrow 1969}.
- ▶ The phenomenon of liquid impact is also of interest in the production of high-speed liquid jets for effective cutting and cleaning operations in industry, and even in the design of lithotripters in medicine.
- ▶ The impact of moving structures on still liquid surfaces gained particular attention in the 1930s with the boom in seaplane construction {WAGNER \Rightarrow 1932}. On the other hand, the impact of moving waters on resting structures is of great importance when designing effective protection for dams against tsunamis and storm surges.
- ▶ *Liquid impact* also encompasses the problems of a body impacting a smooth planar surface²³ (the so-called “water-entry problem”) and of impacting a bulk volume of water. The latter case, known today as a “hydrodynamic ram” (see Sect. 2.4.5), is the oldest example of a liquid impact, and was first demonstrated in France by shooting a bullet into a box filled with water {CARRÉ \Rightarrow 1705}.

(viii) In climatology and anthropology, the term *impact winter* refers to the immediate result of a major asteroid impact similar to the one that occurred around the Cretaceous-Tertiary (or K-T) boundary {Chicxulub Crater \Rightarrow c.65 Ma ago}. This asteroid is believed to have hit off the Yucatán Peninsula with a force of almost one trillion megatons of TNT equivalent. Similar to effects resulting from a *nuclear winter* and a *volcanic winter*, the ultraviolet rays would be blocked by the global dust cloud, choking the planet in icy winter-like conditions for months (or years) and causing an impact winter with widespread death of plants and the large

terrestrial animals that most directly depend on those plants for food. Although the so-called “impact-winter hypothesis” may be popular among the media, little evidence supports it, and other possible extinction mechanisms abound, including global wildfires, greenhouse warming, acid rain, volcanic eruptions, tsunamis and every combination in between.²⁴

(ix) Besides all of the scientific and technical aspects discussed above, impact phenomena also have serious human and economic consequences: since the use of automobiles is steadily growing worldwide, and speeds of transportation are rising, the number of traffic accidents and with it the number of people injured or killed by collisions or impacts has increased dramatically.²⁵ These dangers from modern transportation, recently augmented by the omnipresent risk of terrorist attacks, illustrate the immediate importance of protection measures against shock and impact { \Rightarrow Figs. 4.21–G, H}. They also call for a better understanding and modeling of the behavior of materials under shock loading conditions.

Collisions. The term *collision*,²⁶ as used today in science and even in law and insurance, describes a wide range of processes and phenomena ranging from very high, relativistic velocities observed at the molecular, atomic and subatomic levels to very slow velocities seen in earth sciences, as illustrated in the following examples:

(i) In general physics the term *collision* does not necessarily imply actual contact as in classical mechanics: it rather describes any interaction between particles, aggregates of particles, or rigid bodies in which they come near enough to exert a mutual influence, generally with exchange of energy.²⁷

(ii) In particle physics, a collision describes an interaction between particles rather than between tangible bodies, and one in which momentum is conserved. *Coulomb collisions* are interactions between two moving electric charges at close range {COULOMB \Rightarrow 1785}. The term *collision* has been used throughout the evolution of modern particle physics, for more than 120 years (P. SPENCE 1880; E. RUTHERFORD 1904).²⁸ Elementary (subatomic) particles accelerated to high energies and interacting with matter can either scatter or produce other particles.

²⁴ J. CHAPMAN: *Evidence for impact winter at K/T boundary*. Geotimes (June 24, 2004); <http://www.geotimes.org/june04/WebExtra062404.html>.

²⁵ According to the U.S. Statistics the number of deaths resulting from traffic accidents (road, rail & air) in the United States amounted, for example, to more than 45,000 in 1996, and the number of people injured in the United States every year is several times this.

²⁶ From Lat. *collisio*, meaning “the action of colliding.”

²⁷ S.P. PARKER (ed.): *McGraw-Hill dictionary of scientific and technical terms*. McGraw-Hill, New York (1994).

²⁸ J.A. SIMPSON and E.S.C. WEINER: *The Oxford English dictionary*. Clarendon Press, Oxford (1989), vol. III, p. 487.

²³ R. SKALAK and D. FEIT: *Impact on the surface of a compressible fluid*. Trans. ASME, Ser. B (J. Engng. Ind.) **88**, 325–331 (1966).

The most violent collisions happen when a particle of matter interacts with a particle of *antimatter* {DIRAC \Rightarrow 1928; CHAMBERLAIN & SEGRÉ \Rightarrow 1955; SDI \Rightarrow 1983}. These antiparticles could potentially combine to form antiatoms, and the antiatoms could form antimatter counterparts to every object in the Universe – antistars, antigalaxies. What is more, if a particle of matter collided with a particle of antimatter, they would both be annihilated in an energetic burst of gamma rays, a process called “annihilation.” If a human and an antihuman shook hands, the resulting explosion would be equivalent to 1,000 one-megaton nuclear blasts, each capable of destroying a small city.²⁹ The annihilation of matter with antimatter has also been discussed as a process that could explain the explosive creation of the Universe in a Big Bang, but it has also stimulated science fiction writers.

(iii) In a chemical detonation, explosive molecules are compressed very rapidly and heated by the shock wave, leading to a chain reaction which results in a propagating detonation wave. There is a wide variety of collision events involving large molecules. These can be roughly categorized according to their duration and the amount of energy transferred, ranging from impulsive single collisions and multiple (or complex) collisions, to *supercollision* events.

(iv) In thermodynamics the classical kinetic theory of gases is based on the perfectly elastic collision of molecules or atoms. Its roots date back to first speculations made in the 17th and 18th centuries to explain the nature of heat from the basic laws of motion of “very small, invisible particles” {HOOKE \Rightarrow 1665; Sir NEWTON \Rightarrow 1687} and the kinetic energy of their motion {D. BERNOULLI \Rightarrow 1738}; important improvements to the kinetic theory of gases were made in the 19th century in terms of the statistical motion of molecules by including the theory of probability {MAXWELL \Rightarrow 1867; BOLTZMANN \Rightarrow 1872}.

(v) In chemical kinetics, a branch of physical chemistry, collisions are believed to generate chemical changes, but only if the reaction species – the atoms and molecules – have sufficient internal energy; *i.e.*, a *reactive collision* must be of sufficient energy to break the necessary bonds and must occur in a particular orientation. The rate at which a chemical reaction proceeds is equal to the frequency of these effective collisions. In collision theory models of chemical reactions have been developed to explain the rate laws observed for both one-step and multi-step reactions.

(vi) In mechanical engineering the term *collision* is used to describe a sudden, forceful coming together into direct contact of two moving bodies, resulting in an abrupt change in

motion of at least one of the bodies – *i.e.*, it is used synonymously with the terms *percussion* and *impact*.

- ▶ In a *direct central collision*, the bodies move along the same straight line, and in the special case of a *head-on collision* they move in opposite directions. Everyday examples of head-on collisions with one body at rest and the other in motion include the collision of a golf club and a ball,³⁰ a hammer and a nail head, and pile-driving. The most prominent examples of direct central collision and elastic head-on collision and chain percussion are provided by an apparatus known as “NEWTON’S cradle” (\Rightarrow Fig. 4.4–B).
- ▶ A *side collision* is a collision between two bodies that are not moving along the same straight line, causing their velocity vectors to intersect at the *point of collision*.
- ▶ An *oblique central collision* is a special case of a collision which occurs when the colliding bodies are still confined to the same plane.

(vii) In traffic accidents a *head-on collision* is one where either the front ends of two road vehicles, ships, trains or planes hit each other, or a vehicle hits an object from the front. a *rear-end collision* occurs when a vehicle is hit from behind by another vehicle. It is usually caused by the inattentiveness of the driver of the vehicle, which hits the other vehicle from behind, or by the sudden occurrence of a *traffic shock* {LIGHTHILL & WHITHAM \Rightarrow 1955; \Rightarrow Figs. 4.4–G, H}.

(viii) In stellar dynamics the term *collision* denotes actual physical contact between stars, while the term *encounter* denotes the gravitational perturbation of the orbit of one star by another. In large collisionless stellar systems, such as galaxies, stellar encounters are entirely unimportant when considered over the galaxy’s lifetime; however, in smaller stellar systems such as globular clusters they may play a major role.³¹

- ▶ *Collisional accretion* by gravitational forces is considered to be an important mechanism during the formation of a solar system, particularly during the accretion of small masses into larger ones and eventually the molding of accreting bodies into roughly spherical planets and moons.
- ▶ *Solar wind collision*. The collision of the solar wind with the interstellar plasma slows the supersonic particles emerging from the Sun to subsonic speeds and results in a real astronomical shock wave effect – known as the “termination shock” (see Sect. 2.1.5).

²⁹ G. TARLÉ and S.P. SWORDY: *Cosmic antimatter*. *Scient. Am.* **278**, 36–41 (April 1998).

³⁰ For a high-speed video showing the impact of a metal-driver clubhead on a golf ball see *Gallery of high-speed video applications*. Photron USA Inc., San Diego, CA; <http://www.photron.com/gallery/gallery.cfm>.

³¹ J. BINNEY and S. TREMAINE: *Galactic dynamics*. Princeton University Press, Princeton, NJ (1987).

- ▶ *Stellar collisions* are common in dense star clusters (e.g., globular clusters and the dense cores of young clusters), where they can result in blue stragglers (stars which are hotter and bluer than other cluster stars having the same luminosity) and very massive stars ($> 100 M_{\odot}$, where $M_{\odot} = 1.98 \times 10^{30}$ kg is the mass of the Sun). Direct physical collisions between single stars are rare except in the cores of the densest clusters. Stellar collision researchers distinguish between *parabolic collisions* and *hyperbolic collisions*.³² A third category are collisions occurring between bound partners in a binary star, either because of the perturbation of the pair by a third star (*elliptic collision*), or as a result of “normal” binary evolution (*circular collision*). Numerous computer simulations using Smoothed Particle Hydrodynamics (SPH) have been carried out in order to explore the evolution of collisionally merged stars.³³
- ▶ *Galaxy-galaxy collisions*. Collisions of huge dimensions occur in the Universe when galaxies – i.e., vast systems of stars that also contain gas and dust in various concentrations – interact with each other, thus creating shock waves {Stephan’s Quintet \Rightarrow c. 300 Ma ago; NGC 6240 \Rightarrow 2001; NGC 6745 \Rightarrow 2004}. Galaxy collisions involve a tremendous amount of energy: two objects with masses of the order of 10^{12} solar masses or about 2×10^{42} kg meet with typical relative velocities of about 300 km/s, so the collision energy is of order 10^{53} J. Galaxy collisions are extremely slow by terrestrial standards, with typical time scales of order 3×10^8 years, or 10^{16} seconds. There is little hope of observing any of the dynamics directly. Since in a galaxy collision the tidal gravity forces are responsible for the most significant effects, the term *tidal interaction* is more commonly used in the field.³⁴

When galaxies slam into each other, their individual stars almost never collide. Since the sizes of the stars are very small compared to the average distance between them, the probability of two stars colliding is almost zero. Rather the structure of one or both galaxies gets slowly disrupted, while interior gas condenses to new star forming regions. It is now thought that most galaxies experience several collisions or tidal interactions over the course of their lifetime which are strong enough to profoundly alter their structure and accelerate evolutionary processes. There is also friction between

the gas in the colliding galaxies, causing shock waves that can trigger some star formation in the galaxies.

(ix) In Earth sciences the term *collision* is used to describe the motions and interactions of individual plates of varying size on the surface of the Earth. Although the motions involved are very slow compared to all of the collision events mentioned above (in the range of cm/year), tectonic activity can manifest itself as violent earth/seaquakes and volcanism. {LESSER & FIELD \Rightarrow 1983; Sumatra-Andaman Islands Earthquake \Rightarrow 2004}.

- ▶ *Plate convergence* – a major type of plate boundary behavior, and called “a very slow collision” by geologists – can occur between an oceanic and a largely continental plate, between two largely oceanic plates, or between two largely continental plates (*continental collision*). For example, the collision of India into Asia 50 million years ago caused the Eurasian plate to crumple up and override the Indian plate.³⁵
- ▶ *Collisional orogeny* – the formation of mountains due to the thickening of the continental crust – is caused by the convergence of two plates of the continental lithosphere when the intervening oceanic lithosphere is destroyed by subduction.³⁶

2.1.2 EXPLOSION AND IMPLOSION

Explosions and implosions are extremely rapid phenomena that cause a rapid increase in heat and pressure. In both cases the resulting overpressure, propagating as a wave of condensation, steepens its front, thus turning into a shock wave; i.e., it travels at a supersonic velocity. However, they differ in their geometrical and temporal characteristics: in an explosion, a divergent process, the pressure decays with increasing distance from the explosion source; in an implosion, a convergent process, the pressure increases rapidly with time which can lead to unstable fluid dynamics towards the center of the implosion. Explosions and implosions play an important role during the various stages in stellar evolution.

Explosion. There are three main types of explosions: mechanical, chemical and nuclear explosions. Exploding wires, which belong to a particular class of explosions, are impressive examples of extremely fast changes of physical state: the wire material is rapidly transformed from the solid state into

³² M. FREITAG: *Stellar collisions: quantities and definitions*. Modeling Dense Stellar Systems (MODEST) Working Group 4: *Stellar collisions*; http://www.ast.cam.ac.uk/~freitag/MODEST_WG4/Quantities.html.

³³ Examples of computer animations of “Stellar collisions and cosmic catastrophes” can be watched in the Internet {ASP Conference \Rightarrow 2000}.

³⁴ C.J. STRUCK: *Galaxy collisions*. Physics Reports **321**, 1-137 (1999).

³⁵ U.S. Geology Survey (USGS): *The dynamic Earth: understanding plate motions*; <http://pubs.usgs.gov/publications/text/understanding.html>.

³⁶ P.L. HANCOCK and B.J. SKINNER (eds.): *The Oxford companion to the Earth*. Oxford University Press, Oxford (2000), pp. 148-151.

the gaseous one, generating heat and an expanding plasma that carries a shock wave. With the advent of high-power pulsed lasers, a new type of explosion source was discovered: the breakdown of a gas caused by the attenuation of an intense pulse of focused laser light produces a kind of spark, the “laser spark” {LEE & KNYSTAUTAS \Rightarrow 1969; \Rightarrow Fig. 4.11–G}. However, much higher temperatures and shock wave velocities are achievable than in electric sparks or exploding wires.

The oldest example of an explosion is the explosive rupture of some moist rocks or firewood when exposed to fire, which is actually a steam explosion that may have been noticed by prehistoric man.³⁷ In the Roman Empire, the word “explosion” [Lat. *explosio*] designated a custom used to express displeasure by clapping one’s hands in order to drive (a play) off the stage.³⁸ Beginning with the advent of black powder in Europe in the 14th century, the term *explosion* was mostly applied to the explosion of gunpowder, but later also to the first high explosives. However, an explosion is not necessarily connected with the exothermic reaction of a chemical explosive. With the advent of the *air gun* (or *wind gun*) in the 15th century, imperfectly constructed high-pressure reservoirs attached to the gun provoked mechanical explosions which could seriously endanger the shooter. On the other hand, the rapid disintegration of Prince RUPERT’s drops, which suddenly releases the compressive stress stored internally in the glass, is a comparatively mild explosion and was used as a joke in public demonstrations {HOOKE \Rightarrow 1665; \Rightarrow Fig. 4.16–W}. Mechanical explosions caused by overloading pressurized containers happened quite frequently throughout the Industrial Revolution. Prominent examples include the sudden rupture of boiler walls in steam-boiler explosions, which often resulted in many casualties {SS *Le Rhône* \Rightarrow 1827; ARAGO \Rightarrow 1830; AIRY \Rightarrow 1863; HMS *Thunderer* \Rightarrow 1876; \Rightarrow Fig. 4.21–A}.

In particular, explosions in air have been defined as when the release of energy is rapid and concentrated enough to produce a pressure wave that one can hear {STREHLOW & BAKER \Rightarrow 1976}. Air explosions can be characterized and classified by the generated “blast signature,” *i.e.*, the shock pressure-time profile measured at a certain distance. This depends on the energy rate, the total energy released, and the source geometry. In chemical explosions, some of the total energy released is also transformed into endothermic reactions of

the explosion products, and into radiation. Furthermore, the fission energy that is converted into the shock and the blast in a nuclear aerial explosion is reduced due to the additional production of initial and residual nuclear radiation.³⁹

The geometry of the explosion source strongly determines how quickly the blast pressure decreases from the center of the explosion, and the following basic cases can be differentiated:

- ▶ *1-D explosions*: Classic examples are the bursting membrane in a shock tube {VIEILLE \Rightarrow 1899; W. BLEAKNEY 1943; \Rightarrow Figs. 4.10–A, B}, and gaseous detonations generated in straight tubes, channels and tunnels. Experimental studies of 1-D explosions have been of particular interest during the history of shock wave and detonation physics, because they first allowed theories to be tested using rather simple one-dimensional fluid dynamic models.
- ▶ *2-D explosions*: Exploding wires of sufficient length may approach the ideal of *cylindrical explosions*. Exploding thin metal foils, such as those used to produce planar shock waves in solids in contact with such foils {KELLER & PENNING \Rightarrow 1962; MÜLLER & SCHULTE \Rightarrow 1970}, produce complicated 2-D/3-D wave patterns because of “edge effects.” The irradiation of planar solid targets by ultrashort high-power laser pulses {ASKAR’YAN & MOROZ \Rightarrow 1962; \Rightarrow Figs. 4.11–H, I} or by gamma-ray pulses emitted from nuclear explosions {TRUNIN ET AL. \Rightarrow 1992; \Rightarrow Fig. 4.11–F} are special cases and can produce 2-D blow-offs of target material, thus resulting in an almost planar shock wave propagating into the target.
- ▶ *3-D explosions*: All natural and most man-made explosions are three-dimensional (3-D) and at large distance roughly approach the ideal case of a true spherical shock. Their analytical treatment is a particularly difficult task and has occupied generations of theoretical gas dynamicists. Compared to 1-D and 2-D explosions, 3-D explosions are characterized by a faster decay of the pressure with distance.
- ▶ *Point explosions*: Interest in the gas dynamics of spherical shocks (or blasts) initially focused on finding analytical similarity solutions to the hypothetical *point source* in order to describe the propagation of a strong spherical shock wave, which resulted in the famous Taylor-Sedov similarity solution {G.I. TAYLOR \Rightarrow 1941}.

³⁷ First evidence for the use of fire was found in Chesowanja, East Africa, dating back to 1.5 million years ago. Fire was also used by early man to heat pebbles, which facilitated stone tool production: when put into a fire, a stone can fracture explosively due to any captured moisture turning rapidly into steam.

³⁸ P.G.W. GLARE (ed.): *Oxford Latin dictionary*. Clarendon Press, Oxford (1968), p. 651.

³⁹ For example, for a fission weapon detonating in air at an altitude below 100,000 ft (30.48 km), the fission energy is approximately distributed as follows: about 50% blast and shock, 35% thermal radiation, 5% initial nuclear radiation and 10% residual nuclear radiation. See S. GLASTONE: *The effects of nuclear weapons*. U.S. Atomic Energy Commission, Washington, DC (1962), pp. 8-9.

Any 3-D explosion approaches a *spherical explosion* at a distance that is much larger than the geometrical dimensions of the source. Classic examples of spherical explosions include detonations of spherical charges of chemical explosives or nuclear devices, and electric discharges of capacitor banks over short spark gaps. In the near field, however, these explosive sources may show considerable deviations from an ideal point source. Even in laser sparks, the driving hot plasma in the breakdown phase is not spherical, but rather deformed in the direction of the incident laser pulse {⇒Fig. 4.11–G}. Stimulated by the need for a better insight into the behavior and effects of nuclear explosions, particular attention was paid to the practical flow phenomena accompanying a *finite source explosion*. Considerable theoretical work was done by Harold L. BRODE {⇒1954, 1959 & 1968; see GLASSTONE ⇒1957} of the Rand Corporation in Santa Monica, CA, on the sudden expansion of a sphere of gas, initially pressurized with air or helium. Experimental studies of the spherical explosions of pressurized thin-walled glass spheres, performed by Canadian fluid dynamicists at the University of Toronto Institute of Aerospace, allowed a comparison to be made with BRODE's numerical solution {GLASS & HALL ⇒1957; ⇒Fig. 4.16–F}. They carried out their experiments in a 3-ft-diameter spherical steel tank, which they called a “shock sphere.”

Steam-boiler explosions – the most common examples of mechanical explosions in the past – were often caused by unwittingly exceeding the nominal steam pressure, for example by increasing the weight of the safety valve or through poor maintenance {HMS *Thunderer* ⇒1876}. In industry, such actions also had social causes: in the early era of the industrial revolution most workers were paid by the piece, so the steady availability of steam at full power was of vital interest not only to the factory owner but also to the workman's livelihood. This often resulted in boilers overheating and poor inspections of the technical equipment. Another frequent reason for steam-boiler explosions was the sudden release of a large amount of steam, for example through the operation of the boiler at very low water level, or by starting the engine at full steam. The latter case was vividly described in Mark TWAIN's classical autobiography *Life on the Mississippi* (1883) for the example of the side-wheeler SS *Pennsylvania*, which exploded near Ship Island in the State of Mississippi (resulting in 150 casualties). To reduce the increasing number of disastrous boiler explosions – particularly when operated in close contact with the public, like the ones installed on steam boats {Norwich & Yarmouth steamer ⇒1817; SS *Le Rhône* ⇒1827; SS *Princess* (1859) ⇒Fig. 4.21–A; HMS *Thunderer* ⇒1876} or steam locomotives {Locomotion No. 1 ⇒1828; *Best Friend of Charleston* ⇒1831} – private boiler inspection

unions were founded in several European countries. These bodies supervised the materials used, the construction and the operation of steam-boilers. They were the seeds for modern governmentally operated inspection authorities that act on modern boiler and pressure-vessel standards and on those for other fields of engineering.⁴⁰

Thermohydraulic explosions are violent explosions that can be observed during the contact of a hot liquid with a cool liquid if the temperature of the hot liquid exceeds the homogeneous nucleation temperature of the coolant. This phenomenon, resulting in a violent steam (or vapor) explosion, was named the *fuel-coolant interaction* {Heimaey Eruption ⇒1973}. In the case of water and a hot melt, the term *molten fuel-coolant interaction* has been introduced. As well as being the reason for some severe accidents in industrial plants, molten fuel-coolant interactions were found to play an important role in explosive water-magma interactions (such as in the course of phreatomagmatic volcanic eruptions⁴¹) and in core disruptive accidents of nuclear reactors {Chernobyl ⇒1986}.

Micro steam explosions occur when, for example, matter is exposed to ultraviolet laser radiation of ultrashort duration, and they are used to remove biological tissue from the cornea or skin (for example). Ablation is achieved through a combination of photothermal and photomechanical effects. Thermal denaturation weakens the structural matrix of the tissue, while the explosive transition of water to high-pressure vapor then ruptures the structural matrix, propelling the ablated material from the site of irradiation. Where there is a tissue-air boundary, the second mechanism is clearly seen as an *ablation plume* – a fine mist which contains most of the material ejected during the ablation process {PULIAFITO ET AL. ⇒1987; ⇒Fig. 4.16–Z}. This technique has become an important medical therapy and is widely used in ophthalmology and dermatology.

Chemical explosions may be defined as the sudden or extremely rapid conversion of the solid or liquid bulk of an explosive into gas or vapor which is highly expanded by the heat generated during the transformation and so occupies many times the volume of the original substance. The most frequent chemical explosions are gas explosions.

Gas explosions are defined as a process where combustion of a premixed gas-air cloud causes a detonation, a rapid

⁴⁰ For example, in Germany the privately operated Steam-Boiler Inspection Union [Germ. *Dampfkessel-Überwachungsverein*] which successfully reduced the number of boiler explosions during the period 1870–1900, also stimulated the creation of various official Industrial Inspection Boards [Germ. *Gewerbeaufsichtsämter*] and the privately operated, multipurpose Technical Inspection Union [Germ. *Technischer Überwachungsverein*].

⁴¹ R. BÜTTNER and B. ZIMANOWSKI: *Physics of thermohydraulic explosions*. Phys. Rev. **E57** [III], No. 5, 1–4 (1998).

increase of pressure. In fuel-air mixture at atmospheric pressure, the detonation peak pressure is 15–20 bar. A detonation is the most devastating form of a gas explosion. However, a gas explosion might be caused also by the bursting out of gases or vapors from a vessel under high pressure.

Dust explosion are the oldest man-made chemical explosions, particularly flour dust explosions that occurred in bakeries {MOROZZO \Rightarrow 1785}. Dust explosions occur in modern food processing industries when finely divided combustible matter (e.g., dusts of cereal grain, soy beans, etc.) dispersed into an atmosphere containing sufficient oxygen to permit combustion is accidentally ignited – often by friction-generated flames or electrostatic sparks {American Grain Industry \Rightarrow 1977; First Int. Colloquium on Explosivity of Industrial Dusts \Rightarrow 1978; \Rightarrow Figs. 4.21–D, E}. There is a direct correlation between particle size and its risk of exploding. The smaller the particle, the more reactive the dust. With the beginning of the industrial revolution in the 19th century, dust explosions reached new heights when *coal dust explosions* became a considerable hazard in the coal mining industry {FARADAY & LYELL \Rightarrow 1845; ABEL \Rightarrow 1881}. *Metal dust explosions* {DORSETT ET AL. \Rightarrow 1960}, generally more disastrous than flour and coal dust explosions, became a problem in the 19th century with the advent of new production technologies in the metal industry {Bethlehem Zinc Works \Rightarrow 1854}. More recently, it was even discovered that textile dusts produced from processed and treated nylon fiber may be combustible, ignitable and explosive under certain conditions.

Thermal explosions are complex events that can involve many chemical and physical processes.⁴² For example, thermal explosions occur when matter is evaporated rapidly, such as by focusing a high-power laser on the surface of a solid, which results in a so-called “laser-supported shock wave” {READY \Rightarrow 1963; RAMSDEN & SAVIC \Rightarrow 1964}. In detonics, a thermal explosion is understood as being a rapid chemical reaction that occurs when the temperature in a high explosive exceeds a certain threshold value.

Microexplosions are explosions emitted from very small explosive sources with high energy densities. Since they closely approach the ideal of a point source (previously a mathematical fiction rather than a physical reality), they allow shock and thermal energy to be deposited more economically and precisely at any desired location, thus minimizing the detrimental absorption that occurs upon propagation for focusing shock waves emitted from extended sources {TAKAYAMA \Rightarrow 1983}. The oldest example is the detonation of grains of gold fulminate {CROLL \Rightarrow 1608},

believed to be the first man-made high explosive, which were ignited by the percussion of a hammer in spectacular demonstrations. It was followed by pulsed electric sparks from capacitor discharges, a very comfortable method of generating shock waves in tight spots made possible by the invention of the Leiden jar {VON KLEIST & CUNAEUS \Rightarrow 1745}. In addition, gliding spark discharges {ANTOLIK \Rightarrow 1874; E. MACH & WOSYKA \Rightarrow 1875} and exploding wires {VAN MARUM \Rightarrow 1799; SINGER & CROSSE \Rightarrow 1815} allowed the production of shock waves of any desired geometry. With the advent of high-power pulsed lasers of very short duration in the 1960s, it became possible to focus radiation energy in very small volumes of matter.

Nuclear explosions results from an instantaneous fusion or fission process that can be many thousands (or millions) of times more powerful than the largest chemical detonations. Nuclear explosions provide access to a realm of high-temperature, high-pressure physics not otherwise available on a macroscopic scale on Earth. Such events are accompanied by the emission of electromagnetic radiation over a wide spectral range, such as light, heat, radio waves and gamma rays, generally referred to as “thermal radiation.”

In the Universe, extremely violent explosions occur on a very large scale. The huge and sudden energy release associated with such events exhibits even more complex phenomena than in classic chemical explosions: they emit a broad spectrum of electromagnetic radiation ranging from kilometer-wavelength radio waves to gamma rays with energies of tens of MeV, and the shock waves accelerate energetic particles. Examples include

- ▶ the *Big Bang*, the largest conceivable explosion of an extremely small but incredibly dense and hot fireball occupying a single point in space, which eventually resulted in the enormous but cold and diffuse present-day Universe { \Rightarrow c. 14 Ga ago; NASA-GSFC \Rightarrow 2003};
- ▶ cosmic *gamma-ray bursts*, the most violent explosions in the Universe {Vela Satellites \Rightarrow 1960s; COLGATE \Rightarrow 1967; Gamma-Ray Bursts \Rightarrow 1997};
- ▶ *supernovae* {China \Rightarrow 393; China & Switzerland \Rightarrow 1006; Near & Far East \Rightarrow 1054; BRAHE \Rightarrow 1572; KEPLER \Rightarrow 1604; SHELTON \Rightarrow 1987} and *hypernovae*, very energetic supernovae {Gamma-Ray Bursts \Rightarrow 1997; ROSAT \Rightarrow 1999};
- ▶ *solar flares*, enormous explosions of hydrogen and helium above the Sun’s surface {CARRINGTON & HODGSON \Rightarrow 1859; PARKER \Rightarrow 1961; \Rightarrow Fig. 4.1–V}; and
- ▶ *coronal mass ejections*, huge bubbles of gas that are ejected from the Sun over the course of several hours that can produce interplanetary shocks {Sun & SOHO \Rightarrow 2002}.

⁴² *Thermal explosion: characterization and modeling*. LLNL, Livermore, CA; http://www-cms.llnl.gov/s-t/thermal_explosion.html.

Implosion. An *implosion*⁴³ designates another rapid process which is initially directed opposite to an explosion: the wavefront and the subsequent mass flow first move towards the center of implosion, where they collide with each other and then move outwards; *i.e.*, the latter stages of an implosion also involve explosive behavior. The mathematical treatment of implosions has remained a challenging task. Physically realistic solutions for the center of implosion ($r \rightarrow 0$) – an area of great interest in terms of converging shock waves, but one that is also critical to stability – are particularly difficult to find.

The term *implosion* was apparently coined in the 1880s by the British scientist Sir William THOMSON (Lord KELVIN).⁴⁴ Performing implosion experiments on sealed glass tubes, he observed a fine powder of shattered glass, almost like snow, upon implosion. However, inward-bursting phenomena resulting from the violent collapse of vessels due to external pressure would also have been familiar to early vacuum pioneers (VON GUERICKE 1650; HOOKE 1658).

A very simple implosion system consists of a light fluid surrounded by a spherical shell of dense fluid. Very high pressures compress the system. Converging shock waves passing through the interface cause Richtmyer-Meshkov instability {RICHTMYER \Rightarrow 1960; MESHKOV \Rightarrow 1969}. Rayleigh-Taylor instability {G.I. TAYLOR \Rightarrow 1944} occurs at the end of the implosion, when the dense shell is decelerated by the lighter fluid. Today's implosion devices, such as those applied in laser fusion and nuclear weapons, use highly sophisticated technologies that apply converging shock waves in order to achieve ultrahigh compression of matter.

In a supernova explosion, the *forward shock* sweeps up the interstellar medium, while an inward-propagating shock wave forms when the supersonically expanding neutrino-driven wind collides with the slower supernova ejecta thrown off earlier. This *reverse shock* – a term coined in 1974 by the U.S. astronomer Christopher F. MCKEE⁴⁵ – that moves within the ejecta heats the material ejected in the explosion itself {NASA's Chandra \Rightarrow 2000}. When the reverse shock has begun to reverse the direction of the flow it encounters, it essentially sets up an implosion. The hot ball of gas generated in this manner eventually reaches a state from which it proceeds to expand supersonically and generates an outward-propagating *secondary blast-wave shock*.

The supernova explosion of a massive star leaves behind an imploded stellar core which may form a rapidly rotating neutron star that can be observed many years later as a radio pulsar, releasing a huge amount of energy.

Some cosmological models assume that, when the present expansion of the Universe has come to an end, it may reverse and contract under its own gravitation, thus causing the largest implosion imaginable – the so-called “Big Crunch” {DAVIES \Rightarrow 1994}. Oscillating cosmological models even assume that the Big Crunch is followed by a new Big Bang, thus producing another expanding Universe {FRIEDMANN \Rightarrow 1922}.⁴⁶

2.1.3 CONFLAGRATION, DEFLAGRATION, DETONATION, AND DETONICS

Conflagration. Since the late 17th century, the terms *explosion* and *detonation* were used interchangeably. In 18th-century Germany, the term *detonation* [Germ. *Detonation*] was used to designate a progressive combustion [*Verpuffung*], now known as a “deflagration.” In those times, a progressive combustion was termed a *conflagration* [Brunst or *Verloderung*], a term which today is understood to be a very intense, uncontrolled fire (or an inferno).⁴⁷ However, violent volcanic eruptions were also known as “conflagrations” in England.⁴⁸

With the advent of more sensitive and (particularly) faster diagnostics in the 19th century, it became easier to resolve the complex physical processes of combustion and explosion, and new, more rigid definitions of the terms *deflagration* and *detonation* spread among researchers. Detonation waves and deflagration waves are two distinct types of *combustion waves* which proceed nearly homogeneously in premixed systems in a transient process, although at quite different rates.

Deflagration. A *deflagration*⁴⁹ is a slow combustion process that gives off heat and light but is unable to produce sufficient overpressure to create a shock wave which is strong

⁴³ *Implosion* is an artificial word derived from *explosion* to denote the inwardly directed motion.

⁴⁴ J.A. SIMPSON and E.S.C. WEINER: *The Oxford English dictionary*. Clarendon Press, Oxford (1989), vol. VII, p. 725.

⁴⁵ C.F. MCKEE: *X-ray emission from an inward-propagating shock in young supernova remnants*. *Astrophys. J.* **188**, 335-340 (1974).

⁴⁶ Ancient Greek philosophers advocated at least two important alternatives: PLATO (428–348 B.C.) accepted the common Greek notion of the Universe as a series of world cycles, each having a beginning and ending, while ARISTOTLE (384–322 B.C.), one of his students, postulated an eternal Universe, a steady-state system without beginning or end.

⁴⁷ J.H. ZEDLER (ed.): *Großes vollständiges Universal-Lexicon aller Wissenschaften und Künste*. Zedler, Halle & Leipzig (1732–1754).

⁴⁸ In L. SPALLANZANI's book *Travels in the two Sicilies* [Robinson, London, 1798], vol. I, p. 195, it reads: “But the circumference of the Vesuvian crater is never more than half a mile, even when widest distended, and in its most destructive conflagrations.”

⁴⁹ From Lat. *deflagrare*, meaning “to burn down.”

enough to ignite the fuel. Since the mechanism of inflammation occurs via heat transfer, the speed of the flame front propagating through a flammable gas or vapor is less than the speed of sound in that gas or vapor, often far below the velocity of sound in the burnt gases, and on the order of only some 10 cm/s – *i.e.*, very subsonic. Behind the deflagration front the pressure and density decrease. In the simplest theory deflagrations are described as flow discontinuities, which propagate subsonically {COURANT & FRIEDRICHS \Rightarrow 1948}. However, real deflagration processes are subjected to a variety of instabilities which can significantly influence their flame shape and propagation speed.

The first man-made deflagrations, which took the form of dust explosions, were probably observed in areas where flour had to be milled, stored and processed in large quantities {MOROZZO \Rightarrow 1785}. The term *deflagration* was used as early as 1666 by the British physicist Robert BOYLE.⁵⁰ Black powder – the oldest known explosive {M. GRAECUS \Rightarrow c. 1250; BACON \Rightarrow 1267; SCHWARZ \Rightarrow c. 1380} and now classified as a “low” explosive – is a “deflagrating” explosive. In a *confined deflagration*, the expanding combustion products are confined; for example when the flame is traveling within a pipe.

Deflagration is a common decomposition phenomenon in coal mines and it can occur when the ignition of a mixture of air and firedamp (essentially methane) cannot fully develop into an explosion. Deflagration also plays an important role in *pulsejet engines*, such as the Schmidt tube {P. SCHMIDT \Rightarrow 1930}, in which the fuel is deflagrated rather than detonated. Deflagrations produce peak pressure rises of only a few bars and propagate with subsonic speeds.

Detonation. When a deflagration becomes sufficiently strong, a sudden transition from deflagration to detonation can occur. This transition phenomenon is characterized by very high local pressures, and sometimes very strong damage can be observed at the point of transition to detonation. The term *detonation* designates a violent, supersonic combustion process related to explosive gaseous mixtures and so-called “high explosives,” which may take either liquid or solid form.⁵¹ In England, the term was apparently first used by Roger BACON,⁵² an eminent English 13th-century natural philosopher. Attacking ARISTOTLE’s methodology, he wrote that, for example, the bang generated by hitting a rod (against

a hard object for instance) is not an intrinsic property of the rod but is instead caused by the impact induced by the motion. His new method for achieving knowledge, based exclusively on careful observation and cautious eliminative induction, stimulated the evolution of modern science.

The detonation process in explosives, which is characterized by a high rate of heat generation, is initiated by a shock wave which provokes a strong adiabatic compression, and is also sustained by a rapidly progressing wave. This so-called “detonation wave” {BERTHELOT \Rightarrow 1881; DIXON \Rightarrow 1893}, which appears similar to a strong shock wave, is followed by a combustion zone, in which chemical reactions proceed rapidly to completion. The energy of this reaction maintains constant conditions at the front of the detonation wave, thus leading to a constant detonation rate at or above the velocity of sound in the burnt gases; *i.e.*, on the order of about 2–5 km/s for gases and 6–9.5 km/s for liquid and solid explosives.

In their widely used textbook *Supersonic Flow and Shock Waves*, COURANT and FRIEDRICHS { \Rightarrow 1948} gave a more specific, mathematical interpretation of the terms *deflagration* and *detonation* based on a simple model proposed previously by CHAPMAN { \Rightarrow 1899} and JOUGUET { \Rightarrow 1905}: they demonstrate the characteristic differences of these two processes in terms of the velocities and pressures of the unburnt and burnt gases, noting that “in a *detonation* – in which the pressure increases and the velocity of the gas decreases when the reaction front sweeps over it – the burnt gas is retarded relative to the front,” while “in a *deflagration* – in which the pressure decreases – the gas is accelerated away from the reaction front when the reaction front sweeps over the unburnt gas.”

The term *detonation* was apparently first used in its modern sense by the British chemist Sir Frederick ABEL { \Rightarrow 1869}, who studied detonation effects in guncotton. The French chemist P.E. Marcellin BERTHELOT { \Rightarrow 1870} first termed the rapid motion of the flame front – *i.e.*, the front of the detonation wave – a “shock” [French *un choc*], and in 1881 “explosion wave” [*l’onde explosive*], which appears to have been first taken up in England {DIXON \Rightarrow 1893; CHAPMAN \Rightarrow 1899}. The term *detonation*, which DIXON initially coined for the expression “rate of explosion,” was later also adopted in France {VIEILLE \Rightarrow 1900}.

The term *condensed detonation* refers to the detonation of liquids and solids. Condensed substances that are detonable are more commonly referred to as explosives. The most apparent difference between condensed and gaseous detonations are the detonation pressures, which are a factor of 10^3 to 10^4 higher for condensed explosives than for gases, due to

⁵⁰ J.A. SIMPSON and E.S.C. WEINER: *The Oxford English dictionary*. Clarendon Press, Oxford (1989), vol. IV, p. 386.

⁵¹ From Lat. *detonare*, meaning “to thunder out.”

⁵² R. BACON: *Opera hactenus inedita* (ed. by R. STEELE ET AL.). 16 vols., Clarendon Press, Oxford (1905–1940); vol. VII (1926): *Questiones supra undecimum prime philosophiae Aristotelis*, p. 19.

the large difference in the densities of the media.⁵³ Unlike gaseous detonations, condensed detonations require a wider use of hydrodynamic theory and a fairly precise knowledge of the equations of state of all materials involved in the detonation and sample compression process.

The term *overdriven detonation* refers to an unstable flame front that propagates through a flammable gas or vapor at a speed in excess of the stable detonation velocity. An overdriven explosion may exist during the transition of a combustion process from a deflagration into a stable detonation, which can produce extremely high pressures in a relatively short time frame.

The term superdetonation (or super detonation) designates a detonation that occurs in an explosive precompressed by an initial shock. This type of detonation has a higher pressure and velocity than a detonation in an uncompressed material would have. A superdetonation wave propagates and eventually overtakes the initial shock. After traveling a certain distance, a superdetonation decays to a steady detonation {CAMPBELL \Rightarrow 1961; SHEFFIELD ET AL. \Rightarrow 1989}.

A *retonation* is a wave that moves through the burnt medium from the point of detonation back through burned or burning explosion gases to the ignition source, usually from an area of higher pressure to an area of lower pressure. The term *retonation* was coined in England by DIXON { \Rightarrow 1903} who studied gaseous explosions. Los Alamos physicists have instead used the term *reverse detonation*. Retonation in small sticks of high explosive has been reported by Melvin A. COOK⁵⁴ and others.

Deflagration to Detonation Transition (DDT). In reactive gases this transition is an extremely complex physical process involving deflagrations, shocks and shock reflections, boundary layers, and all of their interactions with each other, and depending on initial and material conditions. Most of the gasdynamic phenomena associated with the development of detonation in an explosive gas – the process commonly referred to as DDT – have been revealed by high-speed laser schlieren cinematography. This very useful diagnostic method helped to elucidate the role played by exothermic centers in the propagation mechanism of detonation and the cause of cellular structures that had been shown to occur inside the soot-coated wall of a cylindrical tube upon the propagation of a self-sustained detonation wave down the tube (\Rightarrow Fig. 4.16–V).

Since the 1950s, it is known that detonation waves in gaseous mixtures show unstable behavior under near-limit detonations, characterized by very large fluctuations of the detonation velocity that can range from 0.4 to 1.8 times the normal Chapman-Jouguet (CJ) value. Based upon measured velocity profiles two propagation modes can be distinguished and have been used to establish a criterion for detonation limits:

- ▶ in a *galloping detonation* the reaction front propagates in an overdriven state, but the velocity decreases until attaining a steady state close to the CJ velocity;
- ▶ in a *stuttering detonation*, however, there exist large velocity fluctuations of the reaction front and a steady state is not reached.

This classification, proposed by detonation researchers at McGill University,⁵⁵ allows a qualitative description of the wide range of velocity fluctuations occurring near the detonation limit.

Flame acceleration and DDT are important phenomena in severe accidents, but DDTs also play an important role in the aerothermodynamics of so-called “pulse detonation engines” (PDEs) {IUTAM Symposium on Combustion in Supersonic Flows \Rightarrow 1997}, in which the fuel is detonated periodically within an engine tube to produce high forward thrust. Pulse detonation engines, in which propagating detonation waves produce peak pressure rises of 30 bar or more and propagate at Mach 5 or faster, have no moving parts in the power production section and are a promising low-cost alternative to turbojet and liquid propellant rocket engines.⁵⁶

In astrophysics, current *Supernova Type Ia* models {BAADE \Rightarrow 1931} invoke a transition from a deflagration wave to a detonation wave.⁵⁷

Detonics. The term *detonics* is of more recent origin and was coined by the Swedish explosive specialists Carl H. JOHANSSON and Per A. PERSSON. In their book *Detonics of High Explosives*, they wrote, “The word *detonics* in the title is chosen in preference to the word detonation to indicate the physics of detonating high explosives and their mechanical effects” {JOHANSSON & PERSSON \Rightarrow 1970}. Their definition has since been widely accepted.⁵⁸

⁵³ S.J. JACOBS: *Recent advances in condensed media detonations*. ARS J. **30**, 151-158 (1960).

⁵⁴ M.A. COOK: *The science of high explosives*. Reinhold, New York (1958), p. 187.

⁵⁵ J.J. LEE ET AL.: *Doppler interferometry study of unstable detonations*. Shock Waves **5**, 175-181 (1995).

⁵⁶ P. PROCTOR: *Pulse detonation technologies advance*. Aviation Week & Space Technology **148**, 48-50 (May 4, 1998).

⁵⁷ A.M. KOHKLOV ET AL.: *Deflagration-to-detonation transition in thermonuclear supernovae*. Astrophys. J. **478**, 678-688 (1997).

⁵⁸ For example, the *Dictionary of science and technology* (C. MORRIS, ed.), Academic Press, San Diego etc. (1992), states on p. 620: “Detonics – the field of study concerned with detonating and the performance of explosives.”

Microdetonics. Condensed phase explosives used in conventional explosive systems have a charge size on the order of a meter or a sizable fraction of a meter. Microdetonics refers to detonation initiation, detonation acceleration (buildup), and detonation curvature effects in small explosive systems. The miniaturization of exploding systems using high explosives in overall dimension not exceeding 10 cm is a more recent development in detonics which promises many new applications, both in military and industry {STEWART \Rightarrow 2002} and in biology and medicine {JAGADEESH & TAKAYAMA \Rightarrow 2002}. Since the explosive's reaction zone length apparently scales down linearly with the reduction in overall device dimension, scientist must select the main charge from one of the short reaction zone explosive materials that lie in the class of primary explosives. Unfortunately, primary explosions are often sensitive to low stimulus and accidental initiation, and alternative concepts of realizing miniature exploding systems are required.

2.1.4 HYDRAULIC JUMP, BORE, SURGE, TSUNAMI, SEICHE, SEA SHOCK, AND ROGUE WAVE

Surface water waves are fascinating natural phenomena that are, in many cases, easily observable with the naked eye, and so they attracted the curiosities of early natural philosophers, who pondered on the complex propagation properties of waves in general. In particular, "water table experiments" were performed to demonstrate and study the fundamental wave effects of propagation and reflection at obstacles that had a variety of shapes.

Water waves belong to a peculiar family of mechanical waves that have wavelengths ranging from a few millimeters (*ripples*) to hundreds of kilometers (*tsunamis* in deep water). They can have a periodic structure (such as that for ordinary surface waves caused by wind action), and can occur recurrently (*breakers*) or at highly predictable times (*tidal waves* and *bores*). Surface waves of large amplitude, propagating with steep wavefronts – such as *tsunamis* (or *seismic sea waves*) in shallow water or *rogue* (or *freak*) waves in deep water – are episodic, relatively rare phenomena which can however cause tremendous damage and loss of life.

Hydraulic Jump. The term *hydraulic jump* designates an abrupt change of depth in a shallow, steady-state flow of water with a free surface, accompanied by turbulent regions in which water depth and flow velocity suddenly change

{ \Rightarrow Fig. 4.1–M}.⁵⁹ For example, a hydraulic jump [Germ. *Wassersprung*] is created at the base of a dam when water at a uniformly shallow depth and moving at high velocity in a channel suddenly enters a region of uniformly high depth and low velocity. Another curious example is the ring-shaped hydraulic jump with a radius of a few centimeters which occurs in a kitchen sink when the tap is left running { \Rightarrow Fig. 4.1–M}. In both examples, the hydraulic jumps are stationary (*i.e.*, nonpropagating) phenomena.

However, hydraulic jumps can also move in shallow water as propagating discontinuities with almost step-like increases in water depth at their fronts. The flow changes its character upon passage through such discontinuities: it partially supercritical and partially subcritical, which in hydraulics is also called a "tranquil-shooting transition."⁶⁰ Hydraulic jumps have a mathematical analog in gas dynamics (steadily progressing one-dimensional compressible supersonic flows in air – *i.e.*, steady 1-D shock waves); small-amplitude gravity waves in water correspond to the acoustic waves in air.

Bore. A *bore* is a high tidal wave that rushes up a narrow estuary or tidal river.⁶¹ The *Severn bore* is produced by a tide that rises to about 18 feet (5.5 m) in an hour and a half. This body of water becomes compressed in the narrowing funnel-shaped Severn estuary, and it is piled up into an advancing wave that extends from bank to bank.

From a physical point of view, a *bore* is a nonstationary hydraulic jump. In nature, it represents a great tidal wave or flood wave with a crested front that forms in rivers and estuaries near the coast, and moves swiftly upstream – popularly described as a traveling "wall of water." The largest bores usually occur around high equinoctial tides. There are three main categories of tidal bores:

- ▶ a *positive tidal bore* of depth $H + h$ running into an adverse current of depth H , the most common form, which results in a tongue of water that moves up a river;
- ▶ a *negative tidal bore* of depth $H - h$ running into still water of depth H , which can form (for example) when the water in a canal is suddenly released by the collapse of a lock gate; and

⁵⁹ An excellent and concise review of shallow-water waves has been given by R.A.R. TRICKER in his article *Water waves*; published in *Encyclopaedia Britannica, Macropaedia*. Benton & Hemingway, Chicago *etc.* (1974), vol. 19, pp. 654–660.

⁶⁰ J.J. STOKER: *Water waves*. Interscience Publ., New York (1957), p. 318.

⁶¹ The origin of the word *bore* is dubious, but it is usually taken to derive from a Scandinavian word, *bdra*, meaning "wave" or "billow." The other name by which the phenomenon is known, *eagre*, is also of unknown origin; see *Encyclopaedia Britannica* (1911).

- ▶ a *solitary wave* {RUSSELL \Rightarrow 1834}, a particular type of wave that only has a crest: its surface profile lies entirely above the still-water level. A solitary wave is formed when a negative bore is followed by an equal positive bore; a positive bore always travels faster than a negative bore of the same height.⁶² Note that a solitary wave is an example of a *wave of translation*; i.e., the water particles advance with the wave and do not return to their original position.

A German encyclopedia⁶³ states that the term *bore* is of Indian origin, and it means “high tide,” since large bores are also observable in the estuary of the Ganges river. The oldest definition of a bore in scientific terms was probably given by the English clergyman and mathematician Samuel EARNshaw { \Rightarrow 1858}, “I have defined a bore to be a tendency to discontinuity of pressure.” In the early 1900s, the term *bore* was sometimes applied to pressure discontinuities in gases as well, such as the *Riemann wave* {Lord RAYLEIGH \Rightarrow 1910}.

Bores are also caused by the collision of two tides, and the term *bore* was reportedly in use as far back as the 17th century,⁶⁴ when it was described as “a boar, as the seamen term it, and violent encounter of two tides coming in.”

The *Severn bore* is one of the most famous among 60 bores around the world and occurs 12 times a year. Its body of water becomes compressed in the narrowing funnel-shaped Severn estuary { \Rightarrow Fig. 4.4–E}, and is piled up into a single advancing wave of up to 2 meters that extends from bank to bank.

Surge. *Surges* are unsteady fluid dynamic phenomena in gases and liquids, characterized by a sudden increase in pressure to an extreme or abnormal value and then a drop from this increased value. They have been observed in nature, on the Earth, and on the Sun as well, but they also exist in man-made fluid-related devices: for example, the shut-down of turbines in hydropower systems can cause the dreaded water hammer in adjacent tunnels and shafts {KAREJSKICH ET AL. \Rightarrow 1898}: this is a shock wave that is followed by a slower moving mass of water, the so-called “mass surge.” In hydrodynamics, a *surge wave* is a wave propagating at the free surface of a liquid, and it is characterized by a sudden increase in the depth of flow across

the wavefront, and severe eddy motion at the wavefront. Hydraulic jumps, bores and tsunamis are sometimes referred to as surge waves. In astrophysics, surges are transient cool plasma jets ejected from small flare-like chromospheric bright points, such as *subflares* (or microflares, small-scale and short-lived flares) and *Ellerman bombs* (tiny fairly bright transient points of light, most often found in emerging flux regions or on the edges of sunspots where the magnetic field is breaking the surface).

Base surges are turbulent mixtures of water vapor or condensed droplets and solid particles at or below a temperature of 100 °C; they travel outward along the ground at hurricane velocities. Base surges were first identified during underwater nuclear bomb detonations at Bikini Atoll in the South Pacific {Operation CROSSROADS \Rightarrow 1946}. A volcanically produced base surge which resulted from water/magma interactions was noted during the explosive eruption of Taal Volcano { \Rightarrow 1965}.

Pyroclastic surges are “hot” base surges consisting of turbulent, low-density clouds of rock debris and air or other gases that have temperatures appreciably above 100 °C and that move over the ground at high speeds {Mt. Pelée \Rightarrow 1902; Mt. St. Helens \Rightarrow 1980}.⁶⁵

Tsunami. The Japanese name *tsunami* – a term that literally means “harbor wave” [*tsu nami*] and has been used in colloquial Japanese since at least the 1890s⁶⁶ – refers to a gravity wave system which forms in the sea following any large-scale, short-duration disturbance of the free surface. It was first proposed for general use by the German-born American geophysicist Beno GUTENBERG { \Rightarrow 1939} instead of the previous misnomer *tidal wave*. The term *tsunami* was eventually adopted by an international scientific committee at the Tsunami Meeting { \Rightarrow 1961} in preference to the term *seismic sea wave*, and it is now defined as “a train of progressive long waves generated in the ocean or a small connected body of water by an impulsive disturbance.”

Tsunamis are very complex, curious natural phenomena, and because of their enormous destructive power they are popularly known as “killer waves.” All large tsunamis can cause severe damage at remote coasts thousands of kilometers from their origin. Prominent examples of so-called

⁶² A quantum or quasi-particle propagating in the manner of a solitary wave is called a “soliton.” This term was coined by the two applied mathematicians Norman J. ZABUSKY and Martin D. KRUSKAL while studying nonlinear interactions among solitary wave pulses propagating in nonlinear dispersive media; see Phys. Rev. Lett. **15**, 240–243 (1965).

⁶³ *Brockhaus Enzyklopädie*. Brockhaus, Wiesbaden, vol. 3 (1967), p. 125.

⁶⁴ J.A. SIMPSON and E.S.C. WEINER: *The Oxford English dictionary*. Clarendon Press, Oxford, vol. II (1989), p. 413.

⁶⁵ *Description: pyroclastic flows and pyroclastic surges*. USGS; http://vulcan.wr.usgs.gov/Glossary/PyroFlows/description_pyro_flows.html.

⁶⁶ Lafcadio HEARN, an Irish-American author who lived in Japan for 14 years, wrote in his book *Gleanings in Buddha-Fields, Studies of Hand and Soul in the Far East* [Houghton & Mifflin, Boston, 1898], “‘Tsunami!’ shrieked the people, and then all shrieks and all sounds and all power to hear sounds were annihilated by a nameless shock ... as the colossal swell smote the shore with a weight that sent a shudder through the hills.”

“teletsunamis” are the Alaskan Earthquakes {⇒1946 & 1964}, the Chilean Earthquake {⇒1960}, and the recent seaquake in the Indian Ocean {Sumatra-Andaman Islands Earthquake ⇒2004}.

Volcanic tsunamis are generated when some of the tremendous amounts of energy produced during volcanic eruptions are transferred to ocean waters or nearby large lakes. James E. BEGÉT,⁶⁷ a volcanologist at Alaska Volcano Observatory, specifies at least nine different mechanisms by which volcanoes produce volcanic tsunamis:

- ▶ volcanic earthquakes;
- ▶ eruptions of undersea volcanoes;
- ▶ movement of pyroclastic flows into the sea, caldera collapse;
- ▶ debris avalanches and landslides;
- ▶ large lahars entering the sea;
- ▶ explosive water-magma interactions caused by the interaction of rising magma and surface water (phreatomagmatic eruptions);
- ▶ coupling between water and turbulent air waves traveling from an explosive eruption; and
- ▶ collapse of lava benches during effusive (non-explosive) lava eruptions.

Mega-tsunamis are defined in the literature as waves that are more than 300 ft (100 m) high; indeed, some tsunami researchers even consider mega-tsunamis to be waves more than a thousand feet (> 300 m) high. The primary sources of such giant tsunamis are the impacts of asteroids with oceans, giant explosive volcanic eruptions, and massive landslides. In 2001, some geophysicists predicted that a future eruption of the Cumbre Vieja volcano on the island of La Palma (one of the Canary Islands, which belong to Spain) may shake loose a gigantic chunk of the mountain’s western flank which would slide into the Atlantic and trigger a 100-m mega-tsunami, devastating the coast of northwest Africa and even the far more remote east coast of North America. However, mega-tsunamis are very rare events and, according to a note disseminated in 2003 by The Tsunami Society,⁶⁸ “no such event – a mega-tsunami – has occurred in either the Atlantic or Pacific oceans in recorded history.”

Tsunami magnitude is defined in terms of the highest wave height at the coast. There are six grades (–1, 0, 1, 2, 3, 4) that depend on the maximum wave height. The first grade (–1)

includes minor tsunamis with wave heights of less than 0.5 m; the highest grade (4) refers to maximum wave heights in excess of 30 meters {IMAMURA ⇒1949}. However, it is very difficult (and in most cases impossible) to measure the height of a tsunami wave directly. The most common method used to determine tsunami wave height is to measure the *tsunami runup height*, the highest vertical point above sea level onshore reached by the wave. Runup heights are characterized by the distance and extent of vegetation killed by salt, and the debris left once the wave has receded. The U.S. National Geophysical Data Center (NGDC) worked out a Tsunami Runup Database, which contains information on the places where tsunami effects have occurred, and it covers both historic and recent tsunami events, ranging from 1500 B.C. to A.D. 2005.⁶⁹

Seiche. The term *seiche* is probably of Swiss origin and denotes rhythmic oscillations of a large water body that depend on the horizontal dimensions and depth of the water.⁷⁰ This phenomenon of standing waves – most commonly caused by a change in atmospheric pressure but also caused by seismic waves – can best be observed in long basins such as in harbors, lakes and bays, when the length of the water body corresponds to one of the natural periods of the basin. In Germany, the pendulum-like water movement is appropriately called “rocking waves” [Germ. *Schaukelwellen*]. It was first studied in the 1890s by the Swiss limnologist François Alphonse FOREL in Lake Geneva (length about ca. 72 km, average width ca. 9 km).

Although the phenomena observed are strictly not discontinuous in nature (periods range between a few minutes to an hour or more), seiches may be reinforced by lunar tides or by selective resonance of the waves excited in the extended body of water. For example, the tide in the Bay of Fundy is a very large seiche generated in the embayment by the tides in the adjacent ocean, because the natural period of the bay is the same as that of the semidiurnal tide. Like bores and shock waves, which can intensify dangerously after oblique reflection at a wall, large-amplitude seiches can produce damage when they collide with dock structures or anchored ships.

Large earthquakes can produce both tsunamis and seiches at the same time, as was first noticed by the German natural philosopher Immanuel KANT {⇒1756} while analyzing remote effects of the Great Lisbon Earthquake {⇒1755}.

⁶⁷ J.E. BEGÉT: *Volcanic tsunamis*. In: (H. SIGURDSSON, ed.) *Encyclopedia of volcanoes*. Academic Press, San Diego etc. (2000), pp. 1005-1013.

⁶⁸ *Mega tsunami hazards*. The Tsunami Society, Honolulu, HI (Jan. 15, 2003); <http://www.sthjourn.org/media.htm>.

⁶⁹ *The NGDC tsunami runup database*. National Geophysical Data Center (NGDC); http://www.ngdc.noaa.gov/seg/hazard/tsmrch_idb.shtml.

⁷⁰ The term *seiche* was apparently first introduced into science by George ROBERTS, who listed it in his *Etymological and explanatory dictionary of the terms and language of geology* [Longman etc., London, 1839].

Sea Shock. Akitune IMAMURA,⁷¹ a Japanese seismology professor at Tokyo Imperial University, discussed the effects of earthquakes on water, such as tsunamis and seiches and another rather more rarely reported phenomenon, *sea shocks*, in his textbook *Theoretical and Applied Seismology*. He wrote, “Earthquake motion upon emerging from the sea-bed passes into the water where it takes the form of elastic waves, transmitting its motion to vessels on the surface. These are ‘sea shocks.’ A ship may receive such shocks without noticing any surface disturbance, although rumbling may at times be heard ... In the great Tōkaidō Earthquake of December 23, 1854, a number of vessels were lost off the coast of Idu, but as tsunamis are impotent at great distances offshore, the only conclusion possible is that the wrecks were caused by sea shocks.” His interpretation was indeed confirmed by later observations. For example, the Lompoc Earthquake that occurred in southern California on November 4, 1927, also produced a seaquake. This resulted in not only in a tsunami but also a violent compressional shock that was transmitted through the water, which stunned fish near Point Arguello and shook at least two ships in the area.⁷²

Rogue wave. A *rogue wave* – sometimes referred to as a “freak” wave or *monster wave* – is a rare event and generally defined as an unexpectedly high sea wave which may come from a direction other than that of the other sea waves. It is a single, massive wall of water that rises up from an apparently calm sea {⇒Fig. 4.1–T}, or it can develop an “enormous hole” when the troughs of several wave trains coincide. Prof. Robert G. DEAN,⁷³ a renowned U.S. coastal engineer and wave hydrodynamicist at the University of Florida, defined rogue waves as waves with heights that exceed the significant wave height of a measured wave train by a factor of 2.2. The significant wave height is defined as the average of the one-third highest waves.

There is now growing evidence, based upon various data sources including satellite imagery, that rogue waves are not produced by landslides or earthquakes: the prevailing theory holds that they can result when strong, high storm waves

slam headlong into a powerful current traveling in the opposite direction. The interaction can push the storm swells together, so that their frequencies superimpose, creating one tremendously powerful wave that can reach a height of 30 meters or more, which suggests that this mysterious phenomenon is responsible for the loss of many ships. Rogue waves may also result from the focusing of wave energy by ocean currents. More recently, an international forum was set up to discuss rogue wave phenomena and theories on their origin {Rogue Waves 2000 Workshop ⇒2000}.

2.1.5 SHOCK AND SHOCK WAVE

In everyday usage, the term *shock* is generally used in medical rather than in a physical or technical sense. With the advent of the first high-voltage generators in the 17th century and the invention of the Leiden jar in the 18th century, the effects of *electric shocks* on humans were widely demonstrated to the public {NOLLET 1746, see VON KLEIST & CUNNEUS ⇒1745} or accidentally experienced by early electricians when experimenting with dangerously high voltages {BENNET ⇒1789}. Up to the mid-20th century, the term *shock* was generally used in relation to medical⁷⁴ and electric phenomena. For example, the 1961 edition of the *Encyclopaedia Britannica* still defined the word “shock” in just two senses: medical and electrical. Over the last 100 years, however, the term *shock* has increasingly been used to refer to a complex set of phenomena related to percussion, shock wave physics, explosion seismology and impact engineering. This wide spectrum of shock-related terms will be discussed in the following.

Shock. The term *shock*, derived from the French word *choc*, is frequently used in mechanical engineering in a more general context which is not strictly related to the definition of a shock wave as given below: it instead implies a degree of suddenness and severity – meaning that the excitation is nonperiodic; *i.e.*, applied in the form of an impulse, a step, or a transient vibration. Coupled into an engineering structure, this results in a mechanical response, the so-called “shock response,” which is an important criterion of a

⁷¹ A. IMAMURA: *Theoretical and applied seismology*. Maruzen, Tokyo (1937), p. 121.

⁷² *Lompoc earthquake*. Southern California Earthquake Data Center (SCEDC), Pasadena, CA; http://www.data.scec.org/chrono_index/lompoc.html.

⁷³ R.G. DEAN: *Freak waves: a possible explanation*. NATO Advanced Research Workshop on Water Wave Kinematics [Molde, Norway, May 1989]. In: (A. TØRUM and O.T. GUDMESTAD, eds.) *Water wave kinematics*. Kluwer, Amsterdam (1990), pp. 609-612.

⁷⁴ In medicine, the word “shock” was originally used as a *physiological* term (designating a state of circulatory collapse caused by an acute loss of blood or fluids from the body), and later also as a *psychological* term (designating a sudden and violent disturbance of emotional or mental equilibrium).

mechanical system related to its ability to resist *impulsive loading*. According to the U.S. researchers John S. RINEHART and John PEARSON, impulsive loading is characterized “by an almost instantaneous, less than a small fraction of a microsecond, rise in load to a quite high but finite value which is followed immediately by a rapid decrease in load; the duration of an impulsive load is usually of the order of microseconds” {RINEHART & PEARSON \Rightarrow 1965}. Impulsive loading may develop when an explosive charge is detonated in intimate contact with a body or when one body impacts against another. Its intensity is usually of a sufficient magnitude to produce extensive fracturing and large permanent distortions in the body upon which it acts.

A *shock wave* is sometimes called a “shock.”

Shock Wave. In the natural sciences, the most common shock-related term is the *shock wave* (also *shock-wave* or *shockwave*).⁷⁵ It describes a mechanical wave characterized by a surface or sheet of discontinuity in which, within a narrow region, the pressure, density, particle velocity and temperature change abruptly. Because a shock wave moves faster than the speed of sound, the medium ahead of the

shock cannot respond until the shock strikes, and so the shock wave falling upon the initially quiescent particles of matter is a supersonic “hydrodynamic surprise” – similar to a person on the ground being overrun by the thunder-like noise of the sonic boom cone originating from a supersonic aircraft or some other type of aerospace vehicle.⁷⁶ In air, a shock wave produced by an explosion and radiating outward from its center is termed a *blast wave*, because it causes a strong wind,⁷⁷ while the term *shock* is often used for such waves occurring in water or the ground, because the effect is like that of a sudden impact.

From the point of view of a fixed observer, shock waves can be divided up into *nonstationary shock waves* and *stationary shock waves*. Examples of nonstationary shock waves are the blast wave originating from an explosion, the muzzle blast from a gun, or the head wave emerging from a body flying at supersonic speed. Stationary shock waves – i.e., motionless shock waves with respect to the observer – are generated in supersonic wind tunnels around a test body at rest {LANGEVIN & CHILOWSKY \Rightarrow 1918}, or behind nozzles when the outflow velocity exceeds the speed of sound {SALCHER & WHITEHEAD \Rightarrow 1889; L. MACH \Rightarrow 1897}. Stationary shock waves are also created when the flow on the suction side of a transonic wing is accelerated to a supersonic velocity. Under certain conditions of illumination passengers of transonic airliners can directly watch this curious phenomenon (\Rightarrow Fig. 4.14–L).

Shock diamonds, a special kind of stationary shock wave, are disk-shaped shock waves formed behind nozzles due to the presence of reflected shock waves in the exhaust stream and shock heating. They are seen frequently in the exhaust jets of aircraft and rocket engines when viewed from the side (\Rightarrow Fig. 4.20–F). Astronomers have observed knots of bright radio emission in jets of ionized gases – astrophysical jets – which emanate from quasars and other galaxies and range from thousands to millions of light-years in length; these may also be caused by shock heating, as in shock diamonds. “Radio jets” are astrophysical jets that can only be observed with radio telescopes. A radio jet typically ends in a “hot spot,” a small region of intense radio emission.

Compared to acoustic waves, which are waves of very small (almost infinitesimal) amplitude, shock waves are “waves of finite amplitude” that can be characterized by six unusual features:

⁷⁵ EULER (\Rightarrow 1759), without yet coining a term, addressed the “size of disturbance” of a sound wave, meaning its amplitude. POISSON (\Rightarrow 1808) described intense sound as the case “where the molecule velocities can no longer be regarded as very small.” STOKES (\Rightarrow 1848) used the term *surface of discontinuity*, and AIRY (\Rightarrow 1848, 1849) described the wave as an “interruption of continuity of particles of air.” RIEMANN (\Rightarrow 1859) used the modern terms *condensation shock* [Germ. *Verdichtungsstoß*] and *condensation wave* [*Verdichtungswelle*] to illustrate the jump-like steepening of the wavefront. EARNSHAW (\Rightarrow 1860) used the terms *positive wave*, to illustrate that the motion of particles is in the direction of wave transmission, and *wave of condensation*, to characterize the increase in density. August TOEPLER (\Rightarrow 1864) was the first to use the term *shock wave* [Germ. *Stoßwelle*] in the present sense; he originated a shock wave from a spark discharge and first visualized it subjectively using a stroboscopic method. He also used the terms *spark wave* [Germ. *Funkenwelle*] and *air percussion wave* [*Lufterschütterungswelle*] interchangeably, but incorrectly used the term *sound wave* [*Schallwelle*]. RANKINE (\Rightarrow 1870) used the terms *abrupt disturbance* and *wave of finite longitudinal disturbance*, and HUGONOT (\Rightarrow 1885) used the term *discontinuity* [French *discontinuité de la vitesse du gaz et de sa pression*]. Ernst MACH and coworkers (1875–1885) used the terms *shock wave*, *Riemann wave* [Germ. *Riemann'sche Welle*], *bang wave* [*Knallwelle*], and *explosion wave* [*Explosionswelle*]. In the specific case of a supersonic projectile, MACH and SALCHER (\Rightarrow 1886) used the terms *head wave* or *bow wave* [Germ. *Kopfwelle*] and *tail wave* [*Achterwelle*]. Ernst and Ludwig MACH also designated a shock wave as being a *Schallwelle großer Excursion* (\Rightarrow 1889), meaning “a sound wave of large amplitude.” VON OETTINGEN and VON GERNET (\Rightarrow 1888), when studying oxyhydrogen explosions, called the detonation wave “*Stoßwelle*.” In France, the term *shock wave* [French *onde de choc*] was first used by VIEILLE and HADAMARD (\Rightarrow 1898), and later by DUHEM (\Rightarrow 1901) and JOUGUET (\Rightarrow 1904). DUHEM also used the terms *partition wave* [French *onde-cloison*], *true Hugoniot wave*, *surface slope* [French *surface de glissement*], and *quasi shock wave* to characterize special types. Discussing the characteristics of shock waves in air, Lord RAYLEIGH (\Rightarrow 1910) used the term *aerial waves of finite amplitude*.

⁷⁶ D.J. HOLLENBACH and C.F. MCKEE: *Astrophysical shock waves*. In: S.P. MARAN: *The astronomy and astrophysics encyclopedia*. Van Nostrand & Reinhold, New York (1992), pp. 623–627.

⁷⁷ For example, at an overpressure of 10 psi (0.69 bar), the maximum wind velocity is about 290 mph (129 m/s); see GLASSTONE (\Rightarrow 1962), p. 107.

- ▶ when the motion is analyzed based on a coordinate system traveling with the shock, then the flow is always supersonic (Mach number $M > 1$) ahead and subsonic ($M < 1$) behind a shock;⁷⁸
- ▶ a pressure-dependent, supersonic velocity of propagation;
- ▶ the formation of a steep wavefront with a dramatic change in thermodynamic quantities such as density, pressure, temperature, and flow speed;
- ▶ for nonplanar shock waves such as spherical blast waves, a strong decrease in the propagation velocity with increasing distance from the center of origin, because some of the energy of the shock wave is expended to heat the medium in which it travels;
- ▶ the entropy {CLAUSIUS \Rightarrow 1865} of the shock-compressed fluid increases and that of the expansion wave decreases compared to the undisturbed fluid. (these changes, however, are small for “weak shock waves”); and
- ▶ nonlinear superposition properties are observed during the reflections and interactions of shock waves.

Furthermore, shock waves have the unique property that they accelerate (quiescent) particles at the shock front. The sudden acceleration of charged particles up to relativistic velocities due to repeated scattering across a shock wave (e.g., generated in supernovae or by the collision of black holes and galaxies) remains the most attractive model for the production of high-energy cosmic rays {HESS \Rightarrow 1912; KRYMSKY \Rightarrow 1977/1978}.

Shock wave intensity – which can be classified into waves of small but finite amplitude (weak shock regime) and waves of large amplitude (strong shock regime) – can be defined in terms of the pressure ratio across the shock front, $\xi = p/p_0$, a quantity which is also called the “shock strength.” Weak shocks for which ξ is barely greater than 1 move approximately with the speed of sound, while strong shocks which are defined by $\xi \gg 1$ always propagate supersonically.⁷⁹ There is no clear definition as to what comprises the weak shock regime in air. Some researchers consider that the overpres-

sure $\Delta p = p - p_0$ ranges from about 0.1 to 5 Pa (1–50 μ bar) in weak shock waves.

It should be mentioned here that in Germany the term *Stoßwelle* (“shock wave”) initially had a different meaning to that invoked today. Throughout the 19th century it designated a seismic sea wave resulting from an earth- or seaquake {KRÜMMEL \Rightarrow 1887}. The modern meaning of the term *shock wave* was not immediately taken up by encyclopedias. For example, in the German *Meyers Konversationslexikon* (1929), a shock wave was still defined as a “tidal wave originated by an earthquake.” Even in the 1960s various prestigious encyclopaedias such as the *Encyclopedia Americana* (1961) and the *Encyclopaedia Britannica* (1962) did not list the term *shock wave*, which may also illustrate the delay between the emergence of a new, rapidly expanding field of science and its acknowledgment and subsequent review by encyclopaedists. Today *shock wave* [French *onde de choc*, Germ. *Stoßwelle* or *Schockwelle*, Span. *onda de choque*, Russ. *ударная волна*] is a clearly defined and well-established term used in science and technology. The huge field of shock and blast waves has now been treated in numerous special encyclopedic articles from different viewpoints for over a decade now, providing the interested layman with an understanding of the peculiar nature of shock waves and their various applications in research and industry.⁸⁰

There are a couple of special shock- and shockwave-related terms in current use that should be mentioned here.

A *reactive shock* is a shock wave supported by an accompanying chemical reaction; the most common example is the

⁷⁸ It appears that the term *supersonic* was introduced into the English literature by Theodore VON KÁRMÁN in a paper published with N.B. MOORE in 1932. The Oxford English Dictionary [Clarendon Press, Oxford (1989), vol. 17, p. 241] refers to a paper published in the *Journal of the Royal Aeronautical Society* in 1934 in which this term was first used. • Note that the term *supersonics* was previously used to designate periodic sound waves with frequencies greater than those audible to the human ear (> 20 kHz).

⁷⁹ From the Rankine-Hugoniot theory, it follows that the propagation velocity of the shock wave, D , can be calculated from the shock strength, ξ , by the formula $D = c_0 [(\xi + \alpha) / (1 + \alpha)]^{1/2}$, where γ is the ratio of the specific heats, c_0 the velocity of sound for the gas at rest, and $\alpha = (\gamma - 1)/(\gamma + 1)$. For air with $\gamma = 1.4$, this yields the simple expression $D = c_0 [(6 p/p_0 + 1)/7]^{1/2}$.

⁸⁰ The following more recent review articles cover shock wave and detonation phenomena:

(i) K.E. GUBKIN: *Explosion*. In: (A.M. PROKHOROV and J. PARADISE, eds.) *Great Soviet encyclopedia*. MacMillan, New York and Collier MacMillan, London, vol. 5 (1979), pp. 124-126.

(ii) S. LIN: *Shock waves in gases*. In: (S.P. PARKER, ed.) *McGraw-Hill encyclopedia of science & technology*. McGraw-Hill, New York etc., vol. 16 (2002), pp. 435-438.

(iii) J.D. ANDERSON JR.: *Flight (aerodynamics)*. In: (R.A. MEYER, ed.) *Encyclopedia of physical science and technology*. Academic Press, New York, vol. 5 (1991), pp. 389-410.

(iv) M. ROSS: *Shock waves and detonations*. In: (R.G. LERNER and G.L. TRIGG, eds.) *Encyclopedia of physics*. VCH, New York etc. (1991), pp. 1121-1124.

(v) R. RASPET: *Shock waves, blast waves, and sonic booms*. In: (M.J. CROCKER, ed.) *Encyclopedia of acoustics*. Wiley, New York etc., vol. 1 (1997), pp. 329-339.

(vi) R.T. BEYER: *Nonlinear acoustics*. In: (G.L. TRIGG, ed.) *Encyclopedia of applied physics*. VCH, New York etc., vol. 1 (1991), pp. 188-194; J.E. Shepherd: *Compressible flows*. Ibid., vol. 4 (1992), pp. 43-69; and Y. HORIE and A.B. SAWAOKA: *Shock waves*. Ibid., vol. 18 (1997), pp. 29-43.

(vii) S.P. SONETT: *Shock waves*. In: (J.H. SHIRLEY and R.W. FAIRBRIDGE, eds.) *Encyclopedia of planetary sciences*. Chapman & Hall, London (1997), pp. 734-736.

detonation wave generated by the detonation of a high explosive {SCHUSTER \Rightarrow 1893; VIEILLE \Rightarrow 1900; CRUSSARD \Rightarrow 1907}.

In a *rarefaction shock* – i.e., a decompressive shock – the pressure behind the front is smaller than the pressure ahead of it. Initially believed to be physically impossible {RIEMANN \Rightarrow 1859; RANKINE \Rightarrow 1869; JOUGUET \Rightarrow 1904; ZEMPLÉN \Rightarrow 1905}, the existence of rarefaction shocks was first predicted by the Soviet theoretical physicist Yakov B. ZEL'DOVICH { \Rightarrow 1946} in substances that have thermodynamic parameters that are close to critical values. This was later also experimentally confirmed in Freon-13 by his countryman Samson S. KUTATELADZE { \Rightarrow 1978}.

A *pseudo-shock*, a term coined by the Italian-born U.S. aerodynamicist Luigi CROCCO { \Rightarrow 1958}, occurs when a supersonic flow is decelerated to subsonic velocities in a duct surrounded by walls. The shape of this λ -type *pseudo-shock* { \Rightarrow Fig. 4.14–H} depends on the Mach number of the flow and the conditions of the boundary layer. The term *pseudo-shock* is barely used nowadays, and has been replaced by the more accurate term *shock wave/boundary layer interaction*.

Micro-shock waves are spherical shock waves with typical radii of only a few millimeters, both in ambient air as well as in water with peak pressures in the range 1–100 MPa (10–1,000 bar). Micro-shock waves in the cm-range, generated by small amounts of high explosives or electric sparks, played an important role in the discovery of the nature of shock waves {E. MACH & WOSYKA \Rightarrow 1875, E. MACH & SOMMER \Rightarrow 1877, E. MACH, TUMLIRZ & KÖGLER \Rightarrow 1878}. With the advent of pulse lasers, underwater micro-shock waves were produced by focused laser beams {BELL & LANDT \Rightarrow 1967}, a method which was taken up in medical therapy by guiding the laser beam in an optical fiber {NAKAHARA & NAGAYAMA \Rightarrow 1999; JAGADEESH & TAKAYAMA \Rightarrow 2002}. However, there exist some limitations of miniaturization. For example, a wave of finite amplitude needs a certain distance to travel until it has steepened up to become a shock wave, and the structure of a shock wave itself which, only a few mean-free-paths thick, is in the microscopic realm. Furthermore, boundary layer effects can no longer be ignored at increasing miniaturization. The miniaturization of shock waves was also inspired by the arrival of the “new sciences” of microtechnology in the 1960s and nanotechnology in the 1980s with features on a scale near one micrometer (10^{-6} μ m) and below hundred nanometers (10^{-7} m), respectively.

A *nanoshock* is a miniature shock wave generated by an ultrashort laser pulse, which can suddenly drive the irradiated material to extreme pressures and temperatures. Since the resulting mechanical transient has a duration of only a few nanoseconds, this shock pulse was termed a *nanoshock* by

Dana D. DLOTT, a U.S. chemistry professor at the University of Illinois. The combination of the nanoshock compression technique with time-resolved molecular spectroscopy enables dynamic effects to be studied at the molecular level in chemistry, biology and medicine {DLOTT \Rightarrow 2000}.

In magnetohydrodynamics, two basic categories of shock waves – *MHD shocks* – are possible:

- ▶ *fast shock waves* with a jump in magnetic pressure acting on the front in the same direction as the jump in gasdynamic pressure, thus resulting in a wave speed greater than the speed of sound in the medium; and
- ▶ *slow shock waves* with drops in magnetic pressure and gasdynamic pressure in opposite directions at the wavefront, leading to a slow wave with a speed below the speed of sound.

It has proven helpful to categorize MHD shocks into two further classes of intermediate shocks.⁸¹ In addition, in terms of the direction of material flow, two types of magnetic shock waves can be differentiated: *longitudinal shocks* and *transverse shocks* {DE HOFFMANN & TELLER \Rightarrow 1950}.

When a body is slowly subjected to a transient temperature gradient, transient thermal stresses are produced that can be predicted by the methods of *thermoelastostatics* {DUHAMEL \Rightarrow 1837}. These stress pulses are not discontinuities according to the definitions of mathematical physics. However, when the change in temperature occurs so rapidly that inertia causes stresses, the resulting dynamic effects can only be predicted by the methods of *thermoelastodynamics* {DANILOVSKAYA 1950, see DUHAMEL \Rightarrow 1837}. This, in fact, generates a *thermal shock* with a propagating jump in stress and strain.⁸² Such intense shock-like stress pulses arise when, for example, the surface of a solid is irradiated by high-intensity ultrashort pulses of laser light {ASKAR'YAN & MOROZ \Rightarrow 1962; READY \Rightarrow 1963; WHITE \Rightarrow 1963} or X-rays, or by the impact of a burst of particles, for example by pulsed electron beams {WHITE \Rightarrow 1963}, pulsed ion beams {BLUHM ET AL. \Rightarrow 1985}, or the neutron flux from a nuclear explosion {TRUNIN ET AL. \Rightarrow 1992; \Rightarrow Fig. 4.11–F}. The effects of the thermoelastic stress produced by pulsed uniform energy deposition can be described by one-dimensional models using thermoelastic theory {OSWALD ET AL. \Rightarrow 1971}.

Thermal shocking is a more general term used in engineering. It designates any equipment or system failure caused by

⁸¹ P.H. ROBERTS: *Magnetohydrodynamics*. In: (G.L. TRIGG, ed.) *Encyclopedia of physics*. VCH, New York etc. (1991), pp. 680–686.

⁸² H.W. BARGMANN: *On the thermal shock parameter in nuclear engineering*. In: *Proc. Conference on the Structural Analysis, Design & Construction in Nuclear Power Plants* [Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brasil, April 1978]. Pós-Graduação em Engenharia Civil, UFRGS, Porto Alegre (1978), pp. 681–688.

a sudden change in temperature. Fracture of rocks by thermal shocking has been used in stone tool fabrication and mining since prehistoric times.

In very strong explosions, such as in nuclear explosions, a particular shock has been observed which precedes the original shock wave along the surface and is termed the *thermal precursor shock* {⇒Fig. 4.16–Q}. This unique shock wave phenomenon is generated by preheating the surface via the thermal radiation prior to the arrival of the shock wave, and was first observed in nuclear explosions {SHELTON ⇒1953; BRYANT, ETHRIDGE & KEEFER ⇒1955}; however, it was also later observed in large-yield chemical explosions {CDRE Suffield ⇒1964}. This effect can also be simulated and demonstrated in laboratory shock tube experiments: a shock wave propagating over a heated layer of gas will refract, and its velocity will increase {⇒Fig. 4.13–E}.

A *radiative shock* is characterized by an intense radiation flux that precedes it. The region compressed by the shock heats up and produces photons that ionize the cold gas in which the shock propagates and thus creates a *radiative-precursor shock wave*. Radiative shock waves play a major role in several astrophysical phenomena, such as star formation, supernovae explosion, and stellar winds. Radiative shocks can also be created in the laboratory, for example, by using energetic pulsed lasers: the shock wave is produced on a millimeter scale in a miniaturized shock tube by a piston which is pushed by a high-power laser pulse. The conversion of laser energy into mechanical energy is achieved by using the ablation of a micrometer-thick plastic layer at the top of the piston. This allows to accelerate the piston up to a high speed in the tube and to launch the shock in the gas (Xe) filling the tube.

Since the 17th century, the term *shock* has also been used in the English-speaking world in connection with earthquakes,⁸³ and it is very common to speak more specifically of a *ground shock* or a *seismic shock* (from the Greek *seismic*, meaning “earthquake”). Today the latter term is used as a synonym for the term *earthquake*,⁸⁴ designating “a sudden motion or trembling in the Earth caused by the abrupt release of slowly accumulated strain.”

In modern seismic exploration, *seismic waves* are also termed *shock waves*, although they are not characterized by the typical features of a shock wave mentioned above. They rather describe a complex mixture of body waves {POISSON

⇒1831} and surface waves {Lord RAYLEIGH ⇒1885; LAMB ⇒1904} which are modified during propagation by absorption, diffraction and reflection features of the various geologic strata. The sudden force that generates them is not an actual blow, but a wrenching snap, as billions of tons of bedrock, twisted and strained out of shape by the accumulated forces exerted over centuries, rupture along a fault plane and lurch back toward an alignment that relieves the stress {REID ⇒1906}. Consequently, seismic shocks are not characterized by high pressures and steep wavefronts as in true shock waves, but rather by very small earth displacements which happen in the elastic regime; *i.e.*, seismic waves can essentially be treated acoustically. With the advent of the generation of artificial earthquakes by strong infrasound sources (*e.g.*, by detonations or the falling of heavy bodies), the terms *shock* and *seismic shock* are now used in a more specific manner, designating the physical effects which originate from the sudden motion or trembling of the Earth.

A variety of shock-related terms were invented during the period marking the emergence of seismology as a scientific field. Many of these are still in use.⁸⁵

- ▶ The terms *principal shock* or *main shock* were suggested for the strongest member of a series of earthquakes (J.F. Julius SCHMIDT 1874).
- ▶ The slighter shocks in a series of seismic waves were termed *accessory shocks*, with those before the principal shock being *preparatory shocks* and those after it *consecutive shocks* (François A. FOREL 1881). The latter two rather historical terms have been replaced by the terms *foreshocks*⁸⁶ and *aftershocks*, which designate a series of small seismic shocks preceding and following a large earthquake within minutes, hours, days or even months, respectively.⁸⁷ In large earthquakes, geological fault slippage may be announced by foreshocks, preparatory processes for the main rupture; these can occur days to months before the main shock. However, it is still the subject of debate among seismologists as to whether these precursor processes will allow the prediction of earthquakes. Underground nuclear explosions can be followed by aftershocks, and some believe that they may trigger impending earthquakes in the vicinity.

⁸³ An early example is given in Daniel DEFOE's famous novel *The life and strange surprising adventures of Robinson CRUSOE* [Taylor, London 1719]: “After ... I found still no more shocks of the earthquake follow I began to be more compos'd.”

⁸⁴ R.L. BATES (ed.): *Glossary of geology*. Am. Geol. Inst., Falls Church, VA (1987), p. 198.

⁸⁵ C. DAVISON: *The founders of seismology*. Arno Press, New York (1978), p. 121.

⁸⁶ In astrophysics, the term *foreshock* designates the region upstream of a collisionless shock (such as the Earth's bow shock), which contains the accelerated ions and associated MHD waves.

⁸⁷ *Encyclopædia Britannica, Micropædia*. Benton & Hemingway, Chicago *etc.* (1974), vol. I, p. 127 and vol. IV, p. 228.

- ▶ *Microseismic shocks* are very small geological disturbances which are normally only detectable with sensitive instruments and are unlikely to cause damage, but are still clearly distinguishable from background noise.
- ▶ The term *shock line* [Germ. *Stoßlinie*] was coined in Austria {HÖFER ⇒1880}. It was used to designate the vertical projection of the trajectory of the seismic discontinuity propagating in the Earth's crust onto its surface.

In the near-field of large chemical and nuclear explosions initiated underground, at the surface or just above ground, the underground compression is no longer elastic, and true *seismic shock waves* are generated. However, they quickly decrease in amplitude with increasing distance from the explosion source.

In astrophysics, the term *termination shock* [Germ. *Endstoßwelle*, French *terminaison choc*] designates the boundary that precedes the heliosphere, where particles from the Sun (the “solar wind”) drop abruptly from supersonic to subsonic speeds and clash with atomic matter from deep space (the “interstellar wind”). The origin of the term *termination shock* is unknown, but may have arisen from the application of the Laval nozzle in steam turbine work in the late 19th century.⁸⁸ This heliospheric shock phenomenon, which is believed to occur about 13 billion kilometers from Earth (or more than two times farther out than Pluto, the most distant planet) is currently being studied “live” via the two Voyager space probes which, after traveling through the Solar System for more than 25 years, have now reached the region where a termination shock is expected by astrophysicists {Voyager 1 & 2 ⇒2003; Voyager 1 ⇒2004}.

The term *terminal jet shock*, another astrophysical term, refers to a galactic jet phenomenon. At the jet terminus two shocks are formed: the *jet shock* (or *terminal Mach disk*), which effectively stops the incoming jet, and the *standoff shock* (or *bow shock*), which acts to accelerate and heat the ambient interstellar medium {M.D. SMITH ET AL. ⇒1985; ⇒Fig. 4.8–L}.

2.1.6 COLLISIONLESS SHOCK WAVES

In the 1950s, theoretical studies carried out by plasma physicists indicated that shock waves could form even in the near-vacuum of outer space, where particle collisions are extremely rare. They proposed that the collective electrical and magnetic properties of plasmas could produce interactions

that take the place of collisions and permit shocks to form. a magnetic field endows collisionless plasmas with elastic properties analogous to those of a dense gas, and so a plasma wave crossing a magnetic field behaves somewhat like an ordinary sound wave. The theoretical analysis of so-called “collisionless shock waves” (or “collisionfree shock waves”) therefore initially followed the ideas developed from earlier research on aerodynamic shocks. The first experimental confirmation was given by Norman F. NESS and his colleagues at NASA's Goddard Space Flight Center. Using data collected from the IMP 1 spacecraft, they detected clear signs that a collisionless shock exists where the solar wind encounters the Earth's magnetic field {NESS ET AL. ⇒1964}.

Shock waves in hot and low-density plasmas are anomalous in classical shock physics in that they cannot be interpreted on the basis of interparticle binary collisions. In hot plasmas, particle-wave interactions generated by fluctuating fields in the plasma dominate over the particle-particle interactions (*collisional shocks*) that dominate in classical fluid dynamics. For example, collisions of charged particles in the solar wind are so rare that they do not affect the formation of the shock or the dissipation of the solar wind's kinetic energy. Shock waves in plasmas have been observed and studied in both laboratory plasmas and space, and they have been simulated in computer-based “experiments.” There are some fundamental differences between ordinary, collision-dominated shocks and collisionless shocks:⁸⁹

- ▶ The plasma is generally not in thermodynamic equilibrium behind the shock.
- ▶ Jump conditions do not completely determine the downstream state.
- ▶ Collisionless shock fronts have widths that are less than – sometimes much less than – typical collisional mean free paths. A good example of such a shock is the Earth's bow shock, where the scale length of the transition region between the upstream and downstream states is several hundreds of kilometers or less, while the mean free path of the solar wind ions is on the order of 10^7 km.⁹⁰
- ▶ The thickness of the shock front also depends upon the direction of the magnetic field.

⁸⁸ Private communication by J. Randy JOKIPII, Regent's Professor at the Dept. of Planetary Sciences, University of Arizona (March 16, 2006).

⁸⁹ J.L. THIFFEAULT: *Collisionless shocks and the Earth's bow shock*. Presented in the Fall of 1994 for a Gas Dynamics astronomy class at Imperial College London; <http://www.ma.imperial.ac.uk/~jeanluc/talks/bowshock.pdf>.

⁹⁰ E.W. GREENSTADT and R.W. FREDRICKS: *Shock systems in collisionless plasmas*. In: (E.N. PARKER ET AL., eds.) *Solar System plasma physics*. North-Holland, Amsterdam (1979); vol. III: *Solar System plasma processes*, p. 5.

Depending on the wind velocity, magnetic field and ion density of the preshock material, shock waves associated with molecular outflows may be of the jump (J) type or the continuous (C) type.

- ▶ If the magnetic field is weak or nonexistent, all components (e.g., atoms, ions, and electrons) have the same velocity. One may then observe a *J-shock*, because thermodynamic quantities such as temperature and density undergo a discontinuity.
- ▶ If the magnetic field is strong enough, it can provoke a partial decoupling of the flows of the different components of the medium through the shock: the charged particles gyrate around the magnetic field lines and are consequently coupled to this field, while the neutral particles are affected only indirectly by the magnetic field, through collisions with the positive ions (and electrons). The magnetic field accelerates the preshock material without producing a sudden jump in the temperature or velocity of the gas. Such a continuous, magnetically dominated shock is called a “C-shock,” as first discussed in 1980 by the U.S. astrophysicist Bruce T. DRAINE.⁹¹

Exploding stars – supernovae – create very strong shocks that speed into the interstellar medium {HUGGINS \Rightarrow 1864} at tens of thousands of kilometers per second, generating interstellar shock waves {DRAINE & MCKEE \Rightarrow 1993} propagating at up to hundreds of kilometers per second in the hot components of the interstellar medium. Using the emission spectrum produced by interstellar shock waves, it is possible to differentiate between C-shocks and J-shocks.

Interstellar shock waves are likely to be responsible for the acceleration of cosmic rays {HESS \Rightarrow 1912; KRYMSKY \Rightarrow 1977/1978}. Elements beyond iron are formed during a supernova explosion and transported by the blast into outer space. They can later be captured into other clouds and become part of new stars and new planets. Future generations of stars formed from this material will therefore start life with a richer supply of heavier elements than the earlier generations of stars.

2.1.7 SHOCK AND VIBRATION

The phrase *shock and vibration* describes a special field of mechanical engineering that is related to a variety of vibration phenomena and their practical countermeasures, such as damping by shock absorbers {1st Symposium on Shock

& Vibration \Rightarrow 1947; Handbook of Shock & Vibration \Rightarrow 1961}. In many practical applications, classical shock and vibration engineering and advanced shock physics converge. For example, in order to better protect personnel carrying large-caliber guns from extreme acoustic and mechanical shock loading, the issues that this problem imposes on gun construction require joint efforts from mechanical engineers to ensure that the enormous recoil momentum and vibrations are efficiently absorbed and from gas dynamicists to reduce the volume of noise produced by the strong muzzle blast.⁹² Since the human body can be regarded as a biological as well as a mechanical system, shock and vibration effects on man are very complex, and so tolerance criteria for shock and vibration exposure are difficult to derive.⁹³

2.1.8 BLAST WAVE, BLAST, AND BLASTING

Finite-amplitude waves in gases – particularly in the atmosphere – are the most common representatives of propagating discontinuities. Although relatively simply structured in comparison to shock waves in solids, it took decades of improvements in diagnostic techniques and theoretical refinements to fully uncover their true properties and to understand the various phenomena associated with the reflections from and interactions with structures and flows that had been previously observed in both laboratory and full-scale experiments.

Blast Wave. A shock wave in air – such as that emitted from an atmospheric explosion, a fired gun or some such phenomenon – is generally referred to as a *blast wave*, because it is accompanied by a strong wind, as felt by a fixed observer when the wave passes by.

While the term *shock wave* is used in a more general manner – to depict a pressure wave with a steep front but where the wave profile is not specified in more detail – the pressure-time profile of an ideal *blast wave* can be characterized

⁹¹ B.T. DRAINE: *Interstellar shock waves with magnetic precursors*. *Astrophys. J.* **241**, 1021-1038 (1980); *Erratum*. *Ibid.* **246**, 1045 (1981).

⁹² The ear is the part of the human body most sensitive to shock and blast injury. For pure tones, the maximum sound level which the ear can tolerate with pain but without immediately being damaged amounts to about 140 dB ref 2×10^{-4} μ bar, corresponding to a pressure of 2 mbar (1 mbar corresponds to 134 dB, 1 bar to 194 dB). The damage response to pulses, however, depends in a complex manner on the rise time, amplitude and pulse duration of the pressure, and there are wide variations in individual susceptibility to ear injuries. The ear is particularly sensitive to short-duration blast waves. Peak pressures of only a few 10 psi (1 psi = 68.9 mbar) can rupture the eardrum, and still smaller pressures can damage the conducting mechanism and the inner ear {HIRSCH \Rightarrow 1968}.

⁹³ H.E. VON GIERKE and D.E. GOLDMAN: *Effects of shock and vibration on man*. In: (C.M. HARRIS, ed.) *Shock and vibration handbook*. McGraw-Hill, New York etc. (1988), pp. 44.1-58.

by its rise time, peak overpressure, positive phase duration, and total wave duration {FRIEDLÄNDER \Rightarrow 1946}. In the most common case of spherical explosions in air originating from chemical explosives, these quantities can be scaled precisely in terms of the released energy {B. HOPKINSON \Rightarrow 1915; CRANZ 1926; KENNEDY \Rightarrow 1946}, and they are related to the masses of standard high explosives, mostly to TNT {HAEUSSERMANN \Rightarrow 1891; DEWEY \Rightarrow 1964; BAKER, WESTINE & DODGE \Rightarrow 1973}. In nuclear explosions, the positive phase duration is longer than that arising from a chemical explosion with the same energy yield.

In astrophysics, a term coined in Germany {ZÖLLNER \Rightarrow 1865}, the shock wave that emerges from a supernova explosion and ejects the star's envelope into interstellar space is also called a "blast wave." A *blast wave shock* results from the interaction of ambient gas with the stellar material ejected by a supernova and this is the shock wave which precedes the ejecta.

The *blast wave accelerator* is a concept that describes the propulsion of a projectile through a gun tube via the sequential detonation of charges of high explosives, which exert a force on the base of the projectile. This concept allows hypersonic velocities (on the order of 10 km) to be obtained, and so it has been discussed as a way to launch materials into space inexpensively {WILSON \Rightarrow 1993}.

Blast. The term *blast* is used as a shorthand for the term *blast wave*, and/or to designate the ignition of gunpowder or other explosive. A blast wave always propagates with supersonic velocity. The steep-fronted pressure wave causes a sudden shock in the surrounding air or ground, and at a sufficiently large distance from the source this approaches spherical geometry. Blast waves are the most common form of shock waves and they are generated in most man-made explosions, ranging from nuclear blasts to the blasts from powerful electric spark discharges, and by other means where energy is suddenly released in a small space, such as in chemical microexplosions and focused laser beams of high intensity and short duration.

The *muzzle blast* [Germ. *Mündungsknall*, French *l'onde de bouche*] is the shock wave produced in the air by the violent eruption of propellant gases, as generated when a projectile exits the muzzle of a gun (which is appropriately described by ballisticians as "uncorking" the barrel). The muzzle blast actually involves a definite sequence of events: it is a system of normal and oblique shock waves that form the boundaries of a central supersonic region in front of the muzzle where the principal expansion and cooling of the gases occurs. This typical barrel shock pattern is called a "shock bottle"

{SLADE \Rightarrow 1946}. The first pictures of this complex shock interaction phenomenon occurred in CRANZ's textbook on ballistics {CRANZ \Rightarrow 1925}.

The muzzle blast is preceded by a less intense precursor blast caused by the piston-like motion of the projectile when it is still moving in the barrel and compressing the air ahead of it. The German ballistician Carl CRANZ was the first to study the evolution of the muzzle blast from a fired rifle cinematographically. His series of pictures clearly show that this precursor is established before the bullet has emerged from the barrel. In the case of supersonic shots, the head wave is generated at the moment when the projectile outruns the front of the blast wave { \Rightarrow Fig. 4.5–L}.

In a volcanic eruption, pyroclastic flows can be generated during the climactic phase when, for example, slope failure unroofs a magma conduit or hydrothermal system, thus generating surges that have been known by volcanologists and geologists as *volcanic blasts* or *hot hurricanes* since 1980 {Mt. St. Helens \Rightarrow 1980; STURTEVANT \Rightarrow 1991}. Accounts of such blast effects arising from explosive volcanic eruptions and observed at different distances were first collected and analyzed from the Krakatau event { \Rightarrow 1883}. Eruption-induced atmospheric shock waves have been discussed in a USGS note which also reviewed violent explosive volcanic eruptions in history and addressed the magnitudes of the blast pressures and energies released.⁹⁴

According to the USGS geologists Dwight R. CRANDELL⁹⁵ and Rick P. HOBLITT, "a volcanic explosion that has a significant low-angle component and is principally directed toward a sector of no more than 180 degrees is referred to as a *lateral blast*. Such a blast may produce a mixture of rock debris and gases hundreds of meters thick that moves at high speed along the ground surface as a pyroclastic flow, pyroclastic surge, or both ... Lateral blasts may affect only narrow sectors or spread out from a volcano to cover a sector as broad as 180 degrees, and they can reach distances tens of kilometers from a vent." Lateral blasts produced by volcanic eruptions may propagate supersonically; however, experimental evidence is difficult to obtain because of the extremely dangerous environmental conditions involved. It is believed that most lateral blasts propagate subsonically (see Sect. 2.3.1).

When a strong blast wave – for example that produced by a large-yield chemical explosion, a nuclear explosion or an explosive volcanic eruption – arrives at its target, it may

⁹⁴ Hazards – Atmospheric shock waves. USGS (1987); http://vulcan.wr.usgs.gov/Hazards/NRC_Definitions/shock_waves.html.

⁹⁵ D.R. CRANDELL and R.P. HOBLITT: *Lateral blasts at Mount St. Helens and hazard zonation*. Bull. Volcanol. **48**, 27-37 (1986).

creat destructive effects known as “blast damage.” The air immediately behind the shock front is accelerated to high velocities and creates a powerful wind. The wind in turn, creates a dynamic pressure against the sides of objects facing the blast. The combination of the pressure jump (called the “overpressure”) and the dynamic pressure causes blast damage; both immediately jump to their peak values when the shock wave arrives. They then decay over a period ranging from a few tenths of a second to several seconds, depending on the strength and yield of the blast and the geometry and dimensions of the object.

There is a definite relationship between the overpressure and the dynamic pressure. The overpressure and dynamic pressure are both the same at 70 psi (4.81 bar), and the wind speed is 1.5 times the speed of sound (about 502 m/s). Below an overpressure of 70 psi, the dynamic pressure is less than the overpressure; above 70 psi it exceeds the overpressure. Since the relationship is fixed, it is convenient to use the overpressure alone as a yardstick for measuring blast effects. At 20 psi (1.38 bar) overpressure, the wind speed is 500 mph (223 m/s), higher than any tornado wind.

The danger from overpressure comes from the collapse of buildings that are not as resilient as most. The violent implosion of windows and walls creates a hail of deadly missiles, and the collapse of the structure above can crush or suffocate those caught inside. City areas are completely destroyed (with massive loss of life) by overpressures of 5 psi (0.34 bar), which produced wind speed of 162 mph (72 m/s) – *i.e.*, close to the peak wind speeds of the most intense hurricanes.⁹⁶ For comparison purposes: the category-five Hurricane Katrina, which devastated New Orleans in August 2005, had an estimated maximum wind speed of about 175 mph (78 m/s) {FUJITA \Rightarrow 1971}.

Blasting. The term *blasting* has been used in mining engineering since the beginning of the 19th century at least, in order to describe the operation of breaking up coal, ore, rock, or other minerals using explosives – also called “shot firing.” However, the use of black powder, now considered a “low” explosive, is much older, dating back to the 16th century {Venetian Mining Industry \Rightarrow 1572}.

Blasting also describes the operation of breaking up ice using chemical explosives {BARNES \Rightarrow 1927}.

2.1.9 GAS DYNAMICS, RAREFIED GAS DYNAMICS, MAGNETOGASDYNAMICS, AND COSMICAL GAS DYNAMICS

Gas Dynamics. This particular branch of fluid dynamics evolved at the end of the 19th century from attempts to understand the fundamentals of high-speed compressible flow through nozzles and passages. Gas dynamics has grown with the development of high-speed flight and has become an area of research for physicists, chemists, applied mathematicians and astrophysicists. Historically, one of the most important areas of application of gas dynamics was also the theoretical treatment of detonation in gases, in particular the description of the fundamental properties of the detonation wave – a reactive shock wave – and the unsteady motion of the detonation products.

The term *gas dynamics* suggests the idea that the field is exclusively related to the state of gaseous matter. However, Kirill P. STANYUKOVICH, an international authority on gas dynamics, proposed to include “the flow of all compressible media, including liquids and solids” (under conditions of high pressures) {STANYUKOVICH \Rightarrow 1955}. Today gas dynamics is understood as “the study of the motion of gases and of the nature and effect of such motion.”⁹⁷ Klaus OSWATITSCH,⁹⁸ a renowned German physics professor who taught gas dynamic at KTH Stockholm and the University of Freiburg, considered gas dynamics to be a generalization rather than a specialization of hydrodynamics, since it was linked to technical thermodynamics through the inclusion of thermal processes, to mathematics by the development of methods for solving hyperbolic differential equations, and to traditional mechanical acoustics by the inclusion of shock waves. Because of these broad links to other branches of science, in the 1950s he recommended that more chairs dedicated to gas dynamics should be established at German universities.

The term *gas dynamics* (or *gasdynamics*) was apparently coined by Jakob ACKERET { \Rightarrow 1927} in his handbook article entitled *Gasdynamik*. However, modern gas dynamics takes a wider, more general view than in the pioneering days and is nowadays concerned with the causes and effects arising from high-speed flows – steady and unsteady, viscous and nonviscous, conducting and nonconducting – for which compressibility is physically significant. Gas dynamics brings together concepts and principles from several branches of science, and

⁹⁶ *Blast damage and injury*. Federation of American Scientists (FAS), Washington, DC; <http://www.cartage.org.lb/en/themes/Sciences/Chemistry/NuclearChemistry/NuclearWeapons/FirstChainReaction/EffectsNucl/Mechanisms.htm>.

⁹⁷ C. MORRIS (ed.): *Dictionary of science and technology*. Academic Press, San Diego etc. (1992), p. 905.

⁹⁸ K. OSWATITSCH: *Die Gasdynamik als Hochschulfach*. Physik. Blätter **9**, 271-272 (1953).

includes mechanics, thermodynamics, aerodynamics, and chemical kinetics.

Besides the term *gas dynamics*, other names have been considered, such as *compressible flow*, *compressible aerodynamics*, *supersonic flow*, *thermofluid dynamics* and *aero-thermodynamics*. However, aside from the more general term *gas dynamics*, only *compressible flow* (beginning at $M > 0.3$; $\Delta P/P > 5\%$) and *supersonic flow* ($M > 1$) are currently used routinely.

In the case of very high temperature flow fields, a complete analysis should be based upon the simultaneous study of both the gasdynamic field and the thermal radiation field. This particular branch of fluid mechanics, created in the 1960s and termed *radiation gas dynamics* {PAI \Rightarrow 1966}, combines ordinary gas dynamics with the physics of radiation. Gas temperatures may be very high and gas densities very low, such as for the hypersonic flow associated with aerospace vehicles (particularly during the reentry of a space vehicle), and for flows associated with nuclear reactions (particularly in the blast wave of a nuclear bomb).

Rarefied Gas Dynamics. This rather new offshoot of gas dynamics, which quickly developed into a large field of its own, covers phenomena in a gas or at a surface in contact with a gas when the gas density becomes sufficiently low that the mean free path is no longer negligibly small compared to the characteristic dimension of the flow geometry. Rarefied gas dynamics touch upon the subject of this book in relation to processes of momentum and energy exchange in high-speed gas-surface interactions during hypersonic flight at high altitudes (e.g., during interplanetary rocket flight or for orbiting satellites), the formation and structure of shock waves and associated boundary layer effects, and the reflection of shock waves at bounding surfaces.

The theory of rarefied gas dynamics is based to a large extent on the familiar kinetic gas theory {MAXWELL \Rightarrow 1878}. A program for the study of these problems was defined by the Chinese-born U.S. engineer Hsue-Shen TSIEN { \Rightarrow 1946}, a well-known aerodynamics specialist who suggested the standard classification of rarefied gas flows based on the Knudsen number $K_n = l/L$, where l is the mean-free path of a molecule, and L is the characteristic length of the object stationed in the flow {KNUDSEN \Rightarrow 1934}. K_n may, in general, take any value. Conveniently, rarefied gas dynamics is subdivided into four different flow regimes:⁹⁹

- ▶ free-molecular flow (extremely rarefied, $K_n \gg 1$);
- ▶ near-free-molecular flow (highly rarefied);
- ▶ transition flow (moderately rarefied); and
- ▶ slip flow (only slightly rarefied, $K_n < 1$).

Flows of highly rarefied gas are studied via the kinetic theory, while flows of slightly rarefied gas are treated from the standpoint of the gas dynamic theory of a continuous medium.

With the advent of the first artificial satellites in the late 1950s, the Soviet Sputnik 1 { \Rightarrow 1957} and the U.S. Explorer 1 (1958), rarefied gas dynamics quickly attracted increasing attention in the study of hypersonic flow and drag problems, and the study of cosmic gases {Int. Symposium on Rarefied Gas Dynamics \Rightarrow 1958}.

Magnetogasdynamics. Studies of the interaction between magnetic fields and moving, electrically conducting gases shed light on a great variety of new phenomena, ranging from laboratory to cosmic dimensions. To unite the three disciplines of gas dynamics, electrodynamics and plasma physics, the term *magnetogasdynamics* was created, apparently in the early 1950s. It embraces most gaseous and compressible media. However, the term *magnetohydrodynamics*, which implies that the subject pertains to applications in water or at least in incompressible fluids, is also frequently used in the literature when referred to the flow of ionized gases in the presence of magnetic fields. Theodore VON KÁRMÁN { \Rightarrow 1959} suggested the more general term *magnetofluidmechanics*, thus embracing both magnetogasdynamics and magnetohydrodynamics. The first monograph dedicated to plasma physics and magnetofluidmechanics appeared in 1963 and was written by Ali Bulent CAMEL,¹⁰⁰ an Italian-born applied scientist and engineer at George Washington University.

Cosmical Gas Dynamics. This particular branch of astrophysics is mainly an outgrowth of classical gas dynamics, rarefied gas dynamics and magnetogasdynamics. Essentially pioneered by American, Soviet and British researchers in the late 1940s, cosmical gas dynamics was initially termed *cosmical aerodynamics*. However, before the establishment of cosmic gas dynamics, flow problems of cosmical dimensions were also treated in *cosmical electrodynamics*.

Cosmical gas dynamics appeared to enter general usage by both astrophysicists and fluid dynamicists in the 1950s. It was used as the title for the 2nd Symposium of Gaseous

⁹⁹ S.A. SCHAAF: *Rarefied gas dynamics*. In: (W.T.H. LOH, ed.) *Modern developments in gas dynamics*. Plenum Press, New York & London (1969), pp. 235-254.

¹⁰⁰ A.B. CAMEL: *Plasma physics and magnetofluidmechanics*. McGraw-Hill series in missile and space technology, McGraw-Hill, New York (1963).

Masses of Cosmical Dimensions { \Rightarrow 1949}, which was renamed the Symposium on Cosmical Gas Dynamics, and was held in 1953 at Cambridge, MA. Gas dynamical effects govern the physics of many objects in the Universe such as

- ▶ the dynamics of interstellar gas and effects of gravitational fields, a branch of astrophysics termed *interstellar gas dynamics*;
- ▶ shock waves caused by supernova and solar flare explosions;
- ▶ shock wave interactions with magnetic fields and high-energy particles;
- ▶ planetary bow waves;
- ▶ extragalactic and stellar jets;
- ▶ red supergiants in their final stage, their explosion into a supernova and subsequent collapse into a neutron star or a black hole; and
- ▶ spinning pulsars, which are remnants of exploded supernovae.

2.2 INITIATION OF PERCUSSION RESEARCH

*If a ball strikes another equal stationary ball, it comes to rest when that has been driven out.*¹⁰¹

Marcus MARCI VON KRONLAND
Prague 1639

IN physics, the course of history usually proceeds from simple to more complicated problems. The mechanical speculations of the ancient Greeks, as principally evoked by the works of ARCHIMEDES, related wholly to statics or to the doctrine of equilibrium. However, their thinking only extended into dynamics along the most unsuccessful paths.¹⁰² Since the earliest times, however, dynamic processes rather than static ones have been of primary concern to man in his daily struggle of life, and they have been applied throughout his evolution in order to improve his tools and weapons, and to make their application more efficient. Dynamics is an entirely modern science that began with Galileo GALILEI's questioning of "why" and "how" the many motions that can be observed take place.

¹⁰¹ See MARCI { \Rightarrow 1639}, *Propositio XXXVII, Porisma I*.

¹⁰² For more on the development of the principles of statics and dynamics, see ERNST MACH's book *The science of mechanics*. Open Court, La Salle, IL (1960).

2.2.1 NATURA NON FACIT SALTUM

*In fact, such a principle of hardness [as assumed by advocates of the Atom in their corpuscular models] could not exist. It is something impossible, contradicting this general law, that nature constantly observes in all its operations. I am talking about this immutable and perpetual order established since the creation of the Universe that can be called the Law of Continuity, according to which everything that takes place does so in infinitely small steps. It seems that common sense dictates that no change can be made through fault; Natura non operatur per saltum; nothing can pass from one extremity to the other without passing through all the degrees in between.*¹⁰³

Johann BERNOULLI
University of Basel 1727

*The third of the abovementioned theorems relates to the continuity of all mechanical effects – in former times a controversial supposition of all physical theories which, freely borrowed from ARISTOTLE, proclaimed to the well-known dogma: natura non facit saltum. However, modern research has also broken seriously through this hitherto always respected stronghold of physical science. This time, these are the principles of thermodynamics which, based upon more recent facts derived from experience, clashed with that theorem, and if all the signs are to be believed, its days are numbered. Indeed, nature seems to make jumps of a rather odd kind... In all cases the quantum hypothesis resulted in the conception that there are changes in nature which occur not steadily but rather explosively. I hardly need to remind you that the discovery and more detailed research of radioactive phenomena have gained considerably in clearness...*¹⁰⁴

Max PLANCK
Friedrich-Wilhelms-Universität, Berlin 1913

The natural sciences – today understood to be a broad spectrum of disciplines concerned with objects or processes that occur in nature, and including fields such as physics, chemistry, biology, geology, astronomy, *etc.* – partly emerged from physics and mechanics of the 17th and 18th century, and grew from the soil of the "harmony of continuity." Mechanics and phenomenological thermodynamics regarded all processes as continuous, at least as a first approximation, and attempted to express them analytically.

¹⁰³ See J. BERNOULLI { \Rightarrow 1727}. The Swiss mathematician and physicist Johann BERNOULLI (1667–1748) was a brother of the mathematician Jakob BERNOULLI (1654–1705) and father of the mathematician and hydrodynamicist Daniel BERNOULLI (1700–1782); for the latter see the Biographies Index.

¹⁰⁴ M. PLANCK: *Neue Bahnen der physikalischen Erkenntnis* [Rede gehalten beim Antritt des Rektorats der Friedrich-Wilhelms-Universität Berlin, am 15. Oktober 1913]. Max PLANCK. *Physikalische Abhandlungen und Vorträge*. Vieweg & Sohn, Braunschweig (1958), vol. III, pp. 65–76.

The conception of the *Principle of Continuity* [Lat. *lex continui*], based upon the thoughts of some Greek philosophers and resumed in the Renaissance {TISSOT \Rightarrow 1613}, was taken up by numerous natural philosophers. For example, in his *Theory of Monads*, the German philosopher, mathematician and physicist Gottfried W. LEIBNIZ¹⁰⁵ developed the idea that each individual substance is subject to a perpetual change of state, leading to the metaphor that “the present is pregnant with the future.” Such changes are without jumps, and the transition of a substance from one state to another is always continuous and orderly. He wrote in his *Nouveaux essais* (1704), “Tout va par degrés dans la nature et rien par sauts.” The Principle of Continuity was also assumed by the German philosophers Johann Gottfried VON HERDER and Friedrich VON SCHLEGEL throughout their sketches of literary history.

This concept certainly affected subsequent generations of natural philosophers in a disadvantageous manner, resulting in their aversion to permit sudden changes to their analysis and mathematical-physical models. For subsequent naturalists it took a further 150 years to accept discontinuities because it involved the abandonment of the continuity principle *Natura non facit saltus* (“Nature does not make leaps”)¹⁰⁶ – i.e., the denial of the discontinuity of dynamic effects. This may be illustrated in the following examples:

- ▶ In classical mechanics, discussions on discontinuous processes and their actual existence were initiated by studying percussion in more detail. The eminent Swiss mathematician Johann BERNOULLI considered it absurd to apply the laws of percussion to hard and perfectly elastic bodies, because upon collision this would result in sudden velocity changes which – as he argued – cannot happen in nature {J. BERNOULLI \Rightarrow 1727; DIDEROT & D’ALEMBERT \Rightarrow 1751; \Rightarrow Fig. 2.1}.
- ▶ The discussions were later extended to discontinuous wave motion, then termed *sound waves of finite amplitude*, and today known as “shock waves.” For early physicists, shock waves were difficult to accept, because they were characterized by a stepped wavefront. In mathematical nomenclature, shock waves are unsteady planes of the first order; i.e., discontinuities where fluid dynamic quantities – such as the density and velocity at both sides of the shock front – differ by

finite amounts.¹⁰⁷ The assumption of discontinuities in analysis, the most powerful instrument of mathematics, did not evolve until the 18th century {EULER \Rightarrow 1748}. It reached its first milestone with the work of Jean B.J. FOURIER (1807), who showed that any arbitrary function – including functions with discontinuities, such as steps – can be expressed by a trigonometric series.

- ▶ Other, more prominent examples in the history of science of permitting discontinuities include so-called “energy leaps” or “energy jumps” in quantum mechanics, based upon the discovery of the energy quantum in 1900 by the German physicist Max PLANCK, which eventually forced scientists to give up on the Principle of Continuity. The British physical chemist David CHAPMAN,¹⁰⁸ cofounder of the first theory of detonation {CHAPMAN \Rightarrow 1899; JOUGUET \Rightarrow 1905}, wrote in 1914, “PLANCK’s quantum law, in a simple form, is this: particles of matter emit and absorb energy not slowly and continuously, but in ‘jerks.’ In other words, the process of emission of energy is assumed in all cases to be analogous to the process which occurs when a molecule changes into an isomeric form. The latter process has always been assumed by chemists to be a sudden one, and therefore accompanied by a sudden evolution of energy. PLANCK’s hypothesis, therefore, is equivalent to the assertion that all energy changes in matter are of the same character as those which occur in chemical change. The discontinuous character of all chemical change has become so familiar to chemists that it has ceased to be regarded as strange, or as needing explanation. Yet PLANCK’s generalization is considered by some physicists to involve the abandonment of the principle – *Natura non facit saltum* – and the denial of the continuity of dynamical effect.”
- ▶ Stimulated by PLANCK’s discovery of the structure of electromagnetic radiation, the Danish physicist Niels H.D. BOHR realized in 1913 that atomic stability is also related to the notion of discontinuity. He postulated that an atom is capable of subsisting in a series of discrete stationary states without radiating energy, and that the radiation of energy occurs only when it makes a complete transition from one stationary state to another by emitting one quantum of energy in the form of electromagnetic radiation.

¹⁰⁵ G.W. LEIBNIZ: *Nouveaux essais sur l’entendement humain* (1704). This essay, which presented a detailed criticism of John LOCKE’s position, was not published during his lifetime; it first appeared in print in *Œuvres philosophiques latines et françaises de feu Mr. DE LEIBNITZ...* (R.E. RASPE, ed.), J. Schreuder, Amsterdam/Leipzig (1765), vol. 3, chap. IV, p. 16.

¹⁰⁶ Instead of the plural *saltus* (“leaps”), the singular *saltum* (“leap”) is often found in the literature.

¹⁰⁷ Discontinuities of the second, third, etc., order are those where only the second, third, etc., local or temporal derivatives of the fluid quantities are unsteady.

¹⁰⁸ D. CHAPMAN: *General and physical chemistry*. Annu. Repts Chem. Soc. **11**, 1-33 (1914).

- ▶ In physics, another important example of discontinuous action relating to atomic stability is *radioactivity* – the spontaneous disintegration of an atomic nucleus by the emission of some form of matter and/or energy. Decay rates of such nuclear processes are characterized by so-called “half-lives.” Measured half-lives range from 3×10^{-7} seconds to 10^{15} years for alpha decay, and from 10^{-3} seconds to 10^{16} years for beta decay. Electromagnetic decay, characterized by the emission of gamma rays, is much faster and usually occurs after on the order of only 10^{-15} seconds – *i.e.*, the emission of gamma rays from nuclei carries away energy and angular momentum in an extremely discontinuous manner.
- ▶ The most strongly discontinuous processes may have happened in the very initial phase of the creation of the Universe which, according to the standard Big Bang model, consisted of a mixture of radiation (photons) and particles at an extremely high temperature. In accordance with the equivalence of mass and energy inherent in Albert EINSTEIN’s Special Theory of Relativity, collisions between high-energy photons would have transformed radiation into particles of matter. Collision processes between sufficiently energetic photons created particle-antiparticle pairs which immediately underwent mutual annihilation.¹⁰⁹
- ▶ In seismology, stationary discontinuities created by changes in chemical composition or physical properties (*e.g.*, phase changes) are marked by a sudden or rapid increase in the speed of seismic waves with depth; *i.e.*, nonpropagating discontinuities can provoke dynamic discontinuities in terms of velocity changes. Classical examples include the *Conrad discontinuity* between the Earth’s upper and lower crust (at a depth of 7.5–8.6 km) and the *Mohorovičić discontinuity*, the boundary between the crust and upper mantle (about 35–50 km below the continents and about 10 km below the oceans).
- ▶ Fractures in solid media represent mechanical discontinuities that strongly affect the propagation of elastic waves either across or along the fracture plane.¹¹⁰ One of the physical models used to analyze the seismic properties of fracture is the *displacement discontinuity*

model, which assumes that the stresses across a fracture are continuous, but that the displacements are not.¹¹¹

- ▶ In contrast to early physicists, most early chemists took the discontinuous, instantaneous character of chemical changes to be self-evident and did not question it. Studies performed in the first half of the 19th century by renowned chemists – *e.g.*, by J. Jakob BERZELIUS, Jean-Baptiste A. DUMAS, Justus VON LIEBIG and Friedrich WÖHLER – revealed that chemical reactions are indeed rather complex processes and might involve a chain of metastable atomic arrangements, so-called “free radicals” {LIEBIG & WÖHLER \Rightarrow 1832}. These phenomena gained great importance when attempting to understand very rapid self-supporting chemical reactions. Prominent examples include chain reactions in detonations {BODENSTEIN \Rightarrow 1913; SEMENOV \Rightarrow 1934} and supersonic combustion {BILLIG \Rightarrow 1959; IUTAM Symposium on Combustion in Supersonic Flows \Rightarrow 1997}.
- ▶ Giving up the rigid Principle of Continuity also opened up new ways of interpreting mutation leaps in genetics. The Swedish botanist Carl VON LINNÉ, attempting to describe and name plants correctly and to group them systematically into categories in his *Philosophia botanica* (1751), considered the species – the basic unit of botany – to be fixed and unchangeable, and concluded that “we can count as many species now as were created at the beginning.”¹¹² Addressing appropriate principles of botanical nomenclature, he wrote: “The fragments of the Natural Method are to be sought out studiously. This is the beginning and the end of what is needed in botany. *Natura non facit saltus*. All plants exhibit their contiguities on either side, like territories on a geographical map.”¹¹³ But the British naturalist Charles Robert DARWIN encountered the motto in a sharp and interesting form posing an alternative meaning of terrible import,¹¹⁴ “Nature makes no leaps, but God does.” Hence, if one wants to know whether something of interest is of natural origin or

¹⁰⁹ Big Bang theory. In: (P. MURDIN, ed.) *Encyclopedia of astronomy and astrophysics*. Institute of Physics, Nature Publ. Group, London *etc.*, vol. 1 (2001), pp. 173–174.

¹¹⁰ L.J. PYRAK-NOLTE and N.G.W. COOK: *Elastic interface waves along a fracture*. Geophys. Res. Lett. **14**, No. 11, 11107–11110 (1987).

¹¹¹ M. SCHOENBERG: *Elastic wave behavior across linear slip interfaces*. JASA **68**, 1516–1521 (1980).

¹¹² S. LINDROTH: *Carl LINNAEUS (or VON LINNÉ)*. In: (C.C. GILLESPIE, ed.) *Dictionary of scientific biography*. Ch. Scribner’s Sons, New York, vol. 8 (1973), pp. 374–381.

¹¹³ C. VON LINNÉ: *Philosophia botanica, in qua explicantur fundamenta botanica*. G. Kiesewetter, Stockholm (1751); Engl. translation by S. FREER: *LINNAEUS’ philosophia botanica*. Oxford University Press, New York (2003); § 77, p. 40.

¹¹⁴ H.E. GRUBER: *DARWIN on man: a psychological study of scientific creativity. Together with DARWIN’s early and unpublished notebooks*. Wildwood House, London (1974), p. 125.

supernatural one must ask, “Did it arise gradually out of that which came before, or suddenly without any evident natural cause?”

2.2.2 FOUNDATION OF DYNAMICS

*Dynamics [French La Dynamique] is the science of accelerating and decelerating forces and the variable motions which they must produce. This science is entirely due to modern time, and GALILEI is the one who has laid the first fundaments.*¹¹⁵

Joseph-Louis LAGRANGE
Paris 1788

The evolution of mechanics began in antiquity, with general reflections on motion, but it then stagnated for a long period until it was resumed during the Renaissance. The birth of “modern times” – characterized by the rediscovery of certain ancient philosophers and, according to Leonardo DA VINCI (1452–1519), an era that was “ruled by numbers” – provoked considerable progress in mathematics, thus enriching the ways in which scientists conceived of phenomena. His countryman, the astronomer, physicist and mathematician Galileo GALILEI (1564–1642), one of the most outstanding representatives of this era and the “founder of modern experimental science,” became widely known for his contributions to the Law of Gravity, which he ingeniously demonstrated using the examples of free fall and inclined throw. He also pondered on the enormous forces of percussion {GALILEI \Rightarrow 1638; \Rightarrow Fig. 4.3–C}. Everyday percussion phenomena, such as a strike with a hammer, allow one to generate tremendous dynamic effects very easily, which can be reproduced by static means only with much greater effort.

The foundations for *dynamics*, laid in the 16th century by GALILEI, quickly grew into a new branch of mechanics. He derived the motion of a ball rolling down an inclined plane, a falling body, a pendulum, and a ball thrown into the air. His important result that applying a force to a body causes its velocity to change were later formulated in Newton’s Second Law of Motion {Sir NEWTON \Rightarrow 1687}. Nearly all subsequent dynamics has been based upon his conclusions.

The German all-round natural philosopher Gottfried Wilhelm LEIBNIZ (1690–1730) substituted kinetic energy for the conservation of movement. In his work *La Monadologie* (“Theory of Monads”), he postulated in 1714 that the states of substances – which he assumed to be individual, indestructible and indivisible, so-called “monads” – can be ordered con-

tinuously into smooth transitional sequences; *i.e.*, all changes occur without jumps (*Lex continui*, 1704), and that the world is a harmonious cosmos, not a chaos. Consequently, his view of dynamic processes excluded discontinuities altogether. Percussion and shock waves, however, are discontinuous natural phenomena that occur widely in the Universe and are related to each other. Figure 2.1 schematically illustrates the generation of such discontinuities. Obviously, an ambitious analytical approach is required to describe the steep gradients of velocities and forces that occur in real percussion processes and the jumps in pressure, density and temperature that occur across the shock front for shock waves.

Classical Percussion Research. Scientific research in mechanical percussion – now generally termed *classical percussion* – did not start until the beginning of the 17th century. Many prominent naturalists of that century contributed to the understanding of percussion. The first significant progress made in this field in the 17th century is illustrated in more detail in the CHRONOLOGY {GALILEI \Rightarrow 1638; MARCI \Rightarrow 1639; DESCARTES \Rightarrow 1644; WALLIS \Rightarrow 1669 & 1670/1671; WREN \Rightarrow 1669; HUYGENS \Rightarrow 1652 & 1668/1669; MARIOTTE \Rightarrow 1671; Sir Isaac NEWTON \Rightarrow 1687; HUYGENS \Rightarrow 1703}. Percussion studies initially used tangible bodies like billiard balls or cannonballs and were mainly based on observations. These early investigations on the nature of percussion revealed that

- ▶ in a closed system, assuming that there is no friction, energy is conserved as kinetic, potential and elastic energy;
- ▶ percussion phenomena are material-dependent, and depend particularly strongly on the hardness of the bodies involved in the collision, which means that percussion can be classified into *elastic percussion* and *inelastic percussion*;
- ▶ in the case of *elastic percussion*, the velocities of the percussion partners can be determined from their masses and their initial velocities by applying the two Laws of Conservation of Momentum and Energy { \Rightarrow Fig. 2.16};
- ▶ in the case of *inelastic percussion* the kinetic energy is partly transformed into heat, but momentum is conserved;
- ▶ in the case of two colliding bodies, the ratio $\Delta c/\Delta v$ of the relative velocities after and before the collision (Δc and Δv , respectively) is constant {Sir NEWTON \Rightarrow 1687}. This quantity depends on the material and geometry of the collision partners and significantly determines the reflection behavior of colliding bodies

¹¹⁵ J.L. DE LAGRANGE: *Mécanique analytique*. Veuve Desaint, Paris (1788), vol. I (1811), p. 221.

{ \Rightarrow Fig. 2.5}. Two hundred years later, this ratio was termed the *coefficient of restitution* e (or ε) { \Rightarrow Fig. 4.3–F} by Lord KELVIN { \Rightarrow 1879}; and

- ▶ the phenomena associated with the percussion are determined by the body's geometry; in particular where it is struck in regard to its center of gravity, leading to the differentiation between so-called “central percussion” and “eccentric percussion” { \Rightarrow Fig. 2.2}.

Center of Percussion. It has been known for a long time that a hammer blow can be transmitted up the arm and an uncomfortable shock is felt when a hammer is held too far from its head. The English mathematician John WALLIS { \Rightarrow 1670/1671} noticed that an impacted body begins to rotate upon experiencing an impulsive force, and concluded that the percussion or striking of a moving body can be greatest at a particular point – the so-called “center of percussion” [Lat. *centrum percussionis*] – in which the whole percussive force of the body can be assumed to be concentrated.

Figure 2.9 illustrates the characteristic features of the center of percussion in a body of mass m freely rotating around a fixed axis and struck at a distance X from the pivot. The distance of the center of percussion to the axis is given by $L_{CP} = \Theta / mL_{CG}$, where Θ is the *moment of inertia* of the body with respect to the axis, and L_{CG} is the distance between the pivot and the center of gravity. Generally, the center of percussion will be away from the center of gravity ($L_{CP} > L_{CG}$) and positioned on a line that connects the pivot center with the center of gravity. In the simple case of a straight bar of uniform cross-section and length L shown here, the center of gravity is $\frac{1}{2}L$ and the center of percussion $\frac{3}{2}L$ away from the pivot – a result which was provided by HUYGENS in his *Horologium oscillatorium* (Paris 1673).

There are numerous practical and scientific applications where the center of percussion plays an important role, for example:

- ▶ *In ballistics.* The ballistic pendulum, which is used to measure projectile velocities, is perhaps the oldest example of the scientific application of the concept of the center of percussion. An optimized ballistic pendulum {CASSINI JR. \Rightarrow 1707; ROBINS \Rightarrow 1740} is constructed such that the bullet hits the pendulum at its center of percussion. The projectile's kinetic energy is then optimally transferred to the pendulum mass, and the impulsive force generated by the projectile impact causes no reaction force at the pivot.¹¹⁶

- ▶ *In hand-held tools.* Percussive tools such as hammers, sledges, axes and adzes are best designed when the center of percussion is placed as close as possible to the tool head, which can be achieved for example by choosing a heavy tool head and a light handle.¹¹⁷ A hammer can only be stopped from jiggling upon use when it is properly held at a certain distance from the tool head.¹¹⁸
- ▶ *In hand-held sports kits.* (i) When a baseball bat (or a cricket bat) strikes the ball at the center of percussion, it both maximizes the kinetic energy of a blow transmitted to the ball and minimizes the sting from the handle in the batsman's hand; *i.e.*, no shock will be felt in his hands {BRODY \Rightarrow 1979}. In the case of an aluminum softball bat of length 0.81 m, the center of percussion is about 0.17 m away from the fat or distal end of the bat { \Rightarrow Fig. 4.3–Y} – somewhat less than one-third of the length of along a cylindrical bar of length L { \Rightarrow Fig. 2.9}, because the center of gravity is further away from the batsman's hand than $\frac{1}{2}L$. (ii) A tennis player wants to hit the ball in such a way as to achieve the greatest momentum transfer to the ball with the least reaction force on his wrist and elbow. When the ball hits the racket at the center of percussion, or the “sweet spot” {BRODY \Rightarrow 1979; HATZE \Rightarrow 1998} of the racket, the rotational reaction on his wrist and elbow is minimized, and therefore the risk of getting “tennis elbow” [*lateral epicondylitis*] is reduced. On the other hand, shock actions produced by shock waves are also routinely used to heal a “tennis elbow” in modern medical therapies {DGST & IGESTO \Rightarrow 1995}.
- ▶ *In hand-held weapons.* A sword will handle effectively (or feel “alive”) if it is balanced properly and the “sweet spot” exhibits the lowest tendency to vibrate. Therefore, the sweet spot is the most effective portion of the blade to strike the target with. A well-designed sword should structurally reinforce the sweet spot in order to reduce “wobbliness.”¹¹⁹ George L. TURNER,¹²⁰ a member of the American Association of Renaissance Martial Arts, has written a long, readable article on the dynamics of hand-held weapons.

¹¹⁶ I. SZABÓ: *Einführung in die technische Mechanik*. Springer, Berlin *etc.* (1959), pp. 324–326.

¹¹⁷ R.S. HARTENBERG: *Hand tools*. In: *The new Encyclopædia Britannica, Macropædia*. Benton & Hemingway, Chicago *etc.* (1974), vol. 8, pp. 605–624.

¹¹⁸ I. SZABÓ: *Repertorium und Übungsbuch der Technischen Mechanik*. Springer, Berlin *etc.* (1960), p. 216.

¹¹⁹ *Discerning a well-made sword*. Sword Forum International (Mesa, Arizona); <http://swordforum.com/sfu/primer/wellmade.html>.

¹²⁰ G.L. TURNER: *Dynamics of hand-held impact weapons*. Association of Renaissance Martial Arts; http://armor.typepad.com/bastardsword/sword_dynamics.pdf.

- *In mechanical engineering.* In the automotive industry, rear axles of the crank and swing type should be constructed such that the center of percussion coincides with the pivot of the stub axle.¹²¹ In a hammer mill, the shock action between the lever and the rotating cam can be minimized by making use of the concept of the center of percussion.^{122, 123}

In the case of hand-held implements, however, more recent studies performed in the United States and Austria have shown that the problem of minimizing shock action in the hand is more complex than the case of a fixed axis of rotation: the point on a hand-held implement that feels “sweetest” is *not* the center of percussion, because the hand, which extends over a finite length of the handle, exerts an opposing force on the handle {HATZE \Rightarrow 1998}.

Vis Viva Controversy. The percussion studies performed in the 17th century resulted in a challenging question on the nature of force. Obviously, the enormous force involved plays a major role in all percussion processes. However, early endeavors to measure the “force of percussion” by comparing it with the pressure of a weight at rest failed {GALILEI \Rightarrow 1638; \Rightarrow Fig. 4.3–C}. Since the force of percussion typically acts during a very brief period of time – an “infinite” force acts for an “infinitesimal” time producing an instantaneous change in the velocity of the impacting body in the limiting case { \Rightarrow Fig. 2.1} – its measurement was not accessible with early diagnostic means (neither were the very short contact times of percussion and temporal deformations). Therefore, early percussion theories such as those proposed by HUYGENS, MARIOTTE, WALLIS, and WREN, relinquished the difficult task of evaluating the enormous instantaneous force from the beginning.

An impressive and characteristic feature of all percussion processes is the *impetus* ($= mv$) of a mass m moving with velocity v , a term coined in the late Middle Ages by the French philosopher Jean BURIDAN in his *Theory of Impetus* to describe the enormous action which a moving mass can provoke {BURIDAN \Rightarrow c.1350}. He correctly theorized that the mover imparts a power proportional to both v and m to the moved object, which keeps it moving. In order to characterize this action of force, 17th-century natural philosophers proposed different physical quantities:

- The French philosopher and mathematician René DESCARTES used the momentum (or impulse) given by mv , a value which he called the “quantity of motion” {DESCARTES \Rightarrow 1644}.
- On the other hand, the German scientist and philosopher Gottfried W. LEIBNIZ { \Rightarrow 1686} favored the quantity mv^2 as a “true measure of force” [Germ. *wahres Kraftmaß*], and he labeled this quantity the “living force” [Lat. *vis viva*; Germ. *lebendige Kraft*] – in contrast to the “dead force” [Lat. *vis mortua*, Germ. *tote Kraft*], which produces no active work (such as forces from weight or static pressure).
- In his Second Law of Motion, Sir Isaac NEWTON recognized force as being associated with the acceleration of a mass {Sir NEWTON \Rightarrow 1687}.
- In his book *Essai d’une nouvelle théorie de la manœuvre des vaisseaux* (“Essay on a New Theory of the Handling of Ships,” Basel 1714), the Swiss mathematician Johann BERNOULLI the Elder exposed the confusion in Cartesian mechanics between force and living force.
- The Scottish mathematician Colin MACLAURIN { \Rightarrow 1724} argued against the mensuration of the forces of bodies by the square of the velocities.

A reconciliation could be attained by comparing the “efficiency of action” [Germ. *Wirkungsfähigkeit*] of a moving body against a force such as gravity. This can be illustrated using the following example: a body thrown up vertically with a velocity v of 2 climbs for a period of time t of 2, but it travels a distance h of 4 against gravity, because $t = (2h/g)^{1/2}$ and $h = v^2/2g$. Hence, when the efficiency of action of a moving body of mass m is measured in relation to the time over which the force acts against gravity, then mv (the momentum or impulse) is the correct quantity. On the other hand, when the efficiency of action is related to the distance traveled h , then $2mgh = mv^2$ (or or *vis viva*) is the correct quantity {HUYGENS \Rightarrow 1668/1669}. Both concepts – based upon the two Laws of the Conservation of Momentum and Energy – are the basis for all theories on percussion and shock waves. Kinetic energy is now taken to represent one-half of the *vis viva*.

The “question of *vis viva*” was used to make claims about what the point of physics should be, what techniques should be used to gain physical knowledge, and what metaphysics made sense.¹²⁴ The *vis viva* dispute dragged on for over half a century. Eventually, it was recognized by the French physicist and mathematician Jean LE ROND D’ALEMBERT { \Rightarrow 1743} who returned to previous debates on this subject in the foreword of

¹²¹ H. FRANKE (ed.): *Lueger Lexikon der Technik*. Dt. Verlagsanstalt, Stuttgart, Bd. 12 (1967): *Lexikon der Fahrzeugtechnik*, p. 653.

¹²² I. SZABÓ: *Einführung in die technische Mechanik*. Springer, Berlin etc. (1959), pp. 334–336.

¹²³ *Hütte* (ed. by Akademischer Verein Hütte, e.V., Berlin). W. Ernst & Sohn, Berlin, vol. I (1931), p. 297.

¹²⁴ M. TERRALL (Dept. of History, UCLA): *Vis viva revisited*. Hist. Sci. **42**, 189–209 (2004).

his treatise *Traité de dynamique* (“Treatise on Dynamics”) that both concepts were two different ways of looking at the same problem: on the one hand, force can be defined in terms of the velocity of an object, on the other hand, in terms of resistance that has to be overcome to stop a moving body – probably having here in mind impact experiments with objects stopped by springs as carried out previously by the Dutch mathematician and experimental physicist Willem Jacob’s GRAVESANDE {⇒1720; ⇒Figs. 2.7, 4.3–G & 4.3–O}. However, in spite of D’ALEMBERT’s clarifying comments, the interest in the *vis viva* controversy among natural philosophers persisted for a long time {WOLLASTON ⇒1805}.

In military applications, measures to increase the *vis viva* and, therefore, the destructive power of a bombardment, were achieved by intuition and practicability rather than as a result of mathematical studies. Throughout the 15th century, individually carved stone cannonballs were increasingly replaced by heavier wrought iron and later cast iron balls, thus leading to the first ballistic revolution. It is interesting to note here that this principle has recently been resumed and refined through the invention of so-called “kinetic energy (KE) projectiles” [Germ. *Wuchtgeschosse*]. Today high-velocity armor-piercing rounds with heavy cores are considered to be the most effective anti-tank weapons. Heavy projectiles are fabricated from high-density materials such as tungsten carbide or depleted uranium (DU). Indeed, DU projectiles are not only very hard, which provides a high penetration efficiency, but they are also pyrophoric – *i.e.*, they react chemically upon impact, causing an explosion inside whatever they penetrate. Furthermore, the depleted uranium used in the Balkans War in the 1990s is being blamed for a number of deaths from leukemia (“Balkans Syndrome”).

Corpuscular Models. A major question that troubled most early natural philosophers was that of the nature of matter. Theories on the constitution of bodies suppose them either to be continuous and homogeneous, or to be composed of a finite number of distinct particles – such as atoms or molecules. In certain applications of mathematics to physical problems, it is convenient to suppose bodies to be homogeneous in order to make the quantity of matter in each differential element a function of the coordinates. On the other hand, molecular theories can be divided into *static theories*, which assume that molecules are at rest in the body, and *dynamic theories*, which suppose the molecules to be in motion, even while the body is apparently at rest {MAXWELL ⇒1867}. In order to explain the properties of matter, any dynamic molecular (or atomic) theory will use a moving particle model, also known as a “corpuscular model.”

The main impetus to develop such a dynamic theory came from Greek philosophers, particularly from DEMOCRITUS (460–370 B.C.) of Abdera and EPICURUS (341–270 B.C.) of Samos, who attempted to explain matter as being composed of invisible atoms. LUCRETIUS (94–55 B.C.), a Roman poet and philosopher, modified and refined these Greek theories {⇒1st Century B.C.}. He described these invisible and impenetrably hard atoms as all moving downwards in infinite space with equal velocities, which suffer an imperceptible change at random times and positions, just enough to allow occasional collisions to take place between the atoms. Curiously enough, this rather modern concept based on infinitely small particles was proposed almost 1700 years before the scientific study of collisions between tangible bodies was initiated during the Renaissance.

The corpuscular hypothesis was widely discussed among 17th-century philosophers in England and France, resulting in an updated version of the atomic philosophies of antiquity:

- ▶ René DESCARTES and Pierre GASSENDI explained natural phenomena in terms of small, invisible particles of matter: DESCARTES proposed in his *Principia philosophiae* (1644) the existence of relatively hard but divisible corpuscles [Lat. *corpusculae*] that filled all space. In contrast, GASSENDI, drawing in his *Syntagma philosophicum* (1658) upon EPICURUS and LUCRETIUS, theorized about indivisible atoms in motion in an extended void.
- ▶ Robert BOYLE said that matter was made up of small corpuscles and explained all natural phenomena through the motion and organization of “primary particles” which move freely in fluids, less freely in solids and which produce corpuscles by coalition. In his treatise *Origin of Forms and Qualities According to the Corpuscular Philosophy* (1666), he advanced a view that, following DESCARTES, avoided taking a stand upon contemporary disputed issues.
- ▶ Robert HOOKE {⇒1665} suggested a corpuscular model of percussion on an atomic level in his *Micrographia*, in order to explain the properties of gases in terms of the motion and collision of atoms.
- ▶ The ideas of Edmé MARIOTTE {⇒1673} regarding the constitution of air and the role of corpuscles in the propagation of sound resulted in a hypothetical corpuscular model.
- ▶ Sir Isaac NEWTON {⇒1687} evolved a corpuscular theory of matter in his *Principia*. Conceiving of the ideal atom as being perfectly hard, he also used a corpuscular model {⇒Fig. 4.4–A} to explain the nature of light and to illustrate that the propagation of sound occurs via percussion from one particle to another.

In the following two centuries, the crude corpuscular model was refined by researchers in France, Switzerland, England and Germany:

- ▶ Daniel BERNOULLI {⇒1738} used NEWTON's corpuscular model in his *Hydrodynamica*, in which he expressed the phenomenon of heat via the velocity of colliding atoms {Joule ⇒1850}, thus producing the first thermodynamic theory of heat.
- ▶ Jean LE ROND D'ALEMBERT {⇒1743} essentially accepted NEWTON's model in his *Traité de dynamique*; however, to explain elasticity he evolved a model of the atom as a hard particle connected to its neighbors by springs. His model, which in some ways represents the archetype of many subsequent shock wave models, stimulated other naturalists to also explain the propagations of other types of mechanical waves, such as those of seismic shocks {DESMAREST ⇒1756}, in the same manner. The mass/spring model was resumed in the 1960s by the Russian shock physicist Lev. V. AL'TSHULER in his shock wave model {⇒Fig. 4.4–D (d)}.
- ▶ NEWTON's corpuscular model stimulated the assumption of “dark stars” (or “black stars”) {MICHELL ⇒1783; DE LAPLACE ⇒1796}, which anticipated the modern concept of “black holes” {WHEELER ⇒1968; Supermassive Black Hole ⇒1994}.
- ▶ Claude-Louis NAVIER {⇒1822} used a corpuscular model to derive the Laws of Motion for continuous media.
- ▶ August Karl KRÖNIG {⇒1856} proposed a corpuscular model consisting of discrete particles that have only translatory motion.
- ▶ Rudolf J.E. CLAUSIUS {⇒1857}, assuming that translational motion alone could not account for all the heat present in a gas, proposed a corpuscular model of translational, rotary and vibratory energy in which collisions can cause transformations of one form of motion into another.
- ▶ James Clerk MAXWELL {⇒1867}, who introduced statistics into thermodynamics, worked out the distribution of velocities among the molecules of a gas and the mean free path between molecular collisions. For gases at near-atmospheric densities, all of the particles spend most of their time moving with a constant speed, called the “thermal speed” {Joule ⇒1850}, and any particle behaves as if it were alone in its container. At any time instant, however, about one particle in 100,000 will be colliding with another particle or with the container walls, and, over a time interval of one

second, each particle of the gas will experience about 10^9 collisions.¹²⁵

The first experimental evidence for the concept that heat is related to the movement of particles was provided by the American-British Count VON RUMFORD {⇒1798}, following his heat and friction experiments. The French chemist Claude-Louis BERTHOLLET {⇒1809} described a percussion experiment that showed that heat could no longer be produced in a metal once hammering produced no further decrease in volume (a decrease that would cause caloric to be expelled like water from a sponge). Therefore, he associated the rise in temperature with a decrease in the volume of a solid body. However, the French engineer Sadi CARNOT rejected BERTHOLLET's explanation of heating by percussion, and in particular the supposed association between a decrease in volume and a rise in temperature {BERTHOLLET ⇒1809}.

The Scottish botanist Robert BROWN {⇒1827} gave the first visual demonstration of the random movement of microscopic particles suspended in a liquid or gas – so-called “Brownian motion.” Experiments performed in 1909 by the French physicist Jean-Baptiste PERRIN confirmed the physical theory of Brownian motion {⇒Fig. 4.4–A}. He was honored with the 1926 Nobel Prize for Physics “for his work on the discontinuous structure of matter, and especially for his discovery of sedimentation equilibrium.”

Newtonian Demonstrator. Edmé MARIOTTE {⇒1676}, an early French natural philosopher and mathematician, came up with the idea of studying the percussion of two balls suspended on long threads {⇒Figs. 4.3–D, G}. This arrangement was based on a famous experiment devised by Marcus MARCI {⇒1639}, an early Bohemian naturalist and physician, where a cannonball would be fired towards a row of other cannonballs which would stop the flying ball fully, but in doing so the last ball of the row would be expelled with a velocity equal to the velocity of the impacting ball {⇒Fig. 4.3–B}. MARIOTTE's set-up, which eliminated detrimental friction effects between ball and table that occurred in MARCI's set-up, opened the door to the construction of spectacular apparatuses demonstrating chain percussion. Sir Isaac NEWTON used a two-ball pendulum with balls of equal as well as different diameters (*i.e.*, masses) to demonstrate his rules of percussion. The eminent Dutch experimental physicist Willem Jacob's GRAVESANDE {⇒1720} devised various percussion machines suitable for demonstrating and quantitatively studying the straight central and oblique central percussion of elastic and inelastic bodies {⇒Figs. 4.3–G, H}.

¹²⁵ M. MCCHESNEY: *Gaseous state*. In: *Encyclopaedia Britannica, Macropaedia*. Benton & Hemingway, Chicago etc. (1974), vol. 7, pp. 914-922.

The multiple percussion pendulum {⇒Fig. 4.4–B} – also known in England as the “Newtonian demonstrator” (or more popularly as “NEWTON’s cradle” or “balance balls”) and in Germany as the “Klick-Klack” (due to its sound) – has been in use since at least the early 18th century in order to demonstrate the phenomenon of *chain percussion*, and exists in almost every modern collection of physical instruments.¹²⁶ Applying a number of balls of equal size, mass and composition, each bifilarly suspended in order to ensure that oscillations occurred in only one dimension, this ingenious set-up quickly became a spectacular system for demonstrating the Laws of Conservation of Momentum and Energy: the only way that momentum and energy can both be conserved is if the number of impacting balls is the same as the number of ejected balls, and if the ejected balls reach the same height as were reached by the impactors. For common table devices the ball impact velocities are in the order of some 100 cm/s.

An extended version of the multiple-ball pendulum, with additional springs arranged between each ball – thus forming a mechanical transmission line, now frequently used for deformable object simulation in engineering and even in medicine – was also proposed in order to demonstrate the propagation of a shock wave {BURTON ⇒1893; AL’TSHULER ⇒1965}. Modern studies have revealed that chain percussion in the Newtonian demonstrator is actually a rather complex process involving nonlinear dispersion and resulting in a unique solitary wave {HERRMANN & SCHMÄLZLE ⇒1981; NESTERENKO ⇒2001}.

2.2.3 FURTHER INVESTIGATIONS

Percussion research reached its next peak in the second half of the 19th century. The German physicist Franz NEUMANN {⇒1885}, the French mathematician Adhémar J.C. DE SAINT-VENANT {⇒1867} and the German physicist Heinrich HERTZ {⇒1882} developed (partly contradictory) percussion theories in which they included HOOKE’s Law of Linear Elasticity {HOOKE ⇒1679}.¹²⁷ This also allowed theoretical determinations of the instantaneous stress distribution or percussion force. However, experimental evidence was difficult to obtain because of the crude high-speed diagnostics available at that time and, with a few exceptions, this topic remained open for investigation by 20th-century percussion researchers.

Hertzian Cone. The German physicist Heinrich HERTZ {⇒1882} theoretically demonstrated that the stress distribution in a plate that is normally impacted by a hard sphere has a conical geometry that extends symmetrically from the point of impact at the surface into the impacted body – the “Hertzian cone” [Germ. *Hertz’scher Kegel*], known among prehistorians as the “bulb of percussion” {⇒Fig. 4.2–A}. The important result obtained by HERTZ confirmed various hypotheses from archaeologists about how handaxes, arrowheads, knives, and other objects made from flint or similarly hard minerals were produced by primitive man via percussion {KERKHOF & MÜLLER-BECK ⇒1969}.

In the Stone Age, the essential elements of stone-tool making were *flakes and cores*: flakes are the relatively thin pieces that are detached under this Hertzian cone angle, and cores are their sources. Flaking can be carried out

- ▶ by percussion, with a pointed hammerstone;
- ▶ by means of a cylindrical hammer – for example, the shaft of a long bone;
- ▶ by pressure; or
- ▶ in the crudest manner, by battering the piece of stone to be flaked against another stone serving as an anvil.

The early stone industries are distinguished from one another by the different methods of tool-making, by the size of the flakes removed, and by the types and variety of tools produced.

Bulb of Percussion. Percussion applied in a small area on the surface of a brittle stone (such as the crypto-crystalline silica rocks chert and flint) typically produces a swelling on the flake at the point where it has been struck, detaching it from the core. This percussion mark is known as the “bulb of percussion” [Germ. *Schlagzwiebel* or *Schlagkegel*; French *bulbe de percussion* or *cône de percussion*]. In particular, among prehistorians and flint-knappers the semi-cones and bulbs are usually termed *positive bulbs of percussion*, and the hollows are termed *negative bulbs of percussion*. In the interest of strict accuracy the words *of percussion* should be altered to *of applied force*, because there are other ways of producing them besides percussion, such as by static pressures {LEAKEY ⇒1934}.

Distinctive kinds of flakes which show direct superposition of positive and negative bulbs of percussion on the interior and exterior flake surfaces are generally attributed to human manufacture. They may be produced in two ways: by being struck from a core from which a primary flake has previously been struck, or by being produced simultaneously

¹²⁶ E.R. JONES and R.L. CHILDERS: *Contemporary college physics*. Addison-Wesley, Reading, MA (1993). • For a demonstration experiment of the multiple-ball pendulum which allows one to select the number of striking balls see <http://www.walter-fendt.de/ph11e/ncradle.htm>.

¹²⁷ R. HOOKE: *De potentia restitutiva* [Lectures]. Martyn, London (1678).

with the primary flake.¹²⁸ Since violent point impacts are extremely rare events in nature, modern archeologists consider stones showing these typical bulb features to be important evidence of man-made stone tools, particularly when these strokes were applied to the stone repeatedly and in a controlled manner, generally in a row in order to provide a cutting edge, as seen on the oldest chopper stones made in East Africa {LEAKEY \Rightarrow c.2.6 Ma}.

Results obtained in modern anthropology have not only illustrated the enormous time span during which percussion played an important role in man's evolution, but also underline the great value of interdisciplinary cooperation in prehistoric research. The French archeologist Jacques BOUCHER DE PERTHES { \Rightarrow 1837}, upon finding a variety of flint tools in the Somme Valley which had been worked on by man, was the first to relate man's antiquity to periods of geological time. His discovery also certified that man had existed far earlier than the widely accepted date of 4004 B.C. – the year of creation according to the Book of Genesis and a chronology written in the 1650s by the Irish Anglican Bishop James USSHER.

The very important phenomenon of a “bulb of percussion” was apparently first correctly described by the Englishman Sir John EVANS,¹²⁹ the cofounder of prehistoric archaeology, who collected and classified flint implements. He wrote, “The character of fracture is at first at the point of impact... in all cases where a splinter of flint is struck off by a blow, there will be a bulb or projection, of a more or less conical form, at the end where the blow was administered, and a corresponding hollow in the block from which it was dislodged. This projection is usually known as the ‘bulb of percussion’ – a term, I believe, first applied to it by the late Dr. Hughes FALCONER, F.R.S.” FALCONER was an English palaeontologist and botanist who supervised the organization of Indian fossils for the British Museum and pursued palaeontological research while traveling in southern Europe.

Sir John EVANS, who searched for traces of early man in Britain, stated the following important conclusion: “If on a splinter of flint such a bulb occurs, it proves that it must have resulted from a blow, in all probability, but not of necessity, given by human agency; but where the bulb is on the principal face, and analogous depressions, or portions of them, are visible on the several other faces, and at the same end of a flake, all of them presenting the same character, and in a definite arrangement, it is in the highest degree probable that such a combination of blows must be the result of de-

sign, and the features presented are almost as good as a warrant for the *human origin of the flake* as would be the maker's name upon it.”

Conchoidal Fracture. Various fine-grained rocks show typical *conchoidal fracture* which is a smooth but curved fracture surface resembling the interior surface of a shell – a curious phenomenon explained by the interaction and reflection of shock waves resulting from percussion. Such waves run through the stone along a curved route, detaching a curved flake. Rocks of this type include many lavas, as well as obsidian, flint and chert, and they were used in tool-making from the earliest times in the evolution of man.¹³⁰ To gain further insights into the past, the basics of stone tool technology are now being studied by performing “experimental archeology.” Today many prehistoric museums demonstrate the art of flint knapping to their visitors.

Percussion Figures. When a blow from a sharp point is applied to the surface of a crystal, a fracture pattern is produced which is closely related to the internal structure of the crystalline lattice {REUSCH \Rightarrow 1867}. This “percussion figure” [Germ. *Schlagfigur*] is characterized by lines that are parallel to the plane of symmetry of the crystal. For example, a sharp blow applied to a cleavage flake of mica produces a six-rayed star of cracks, while a point-loaded cubic crystal such as rock salt produces a four-rayed fracture pattern { \Rightarrow Fig. 4.3–N}. These cracks coincide with planes of easy separation or of gliding in the crystal. Percussion figures are especially useful to mineralogists since they allow them to quickly determine the crystallographic orientations of some minerals.

Percussion Marks. These are crescent-shaped scars produced on hard, dense pebbles (especially ones of chert or quartzite) by a sharp blow, as by the violent impact of one pebble on another.

- Percussion marks are also created by rock to rock collisions and may be indicative of high-velocity flows.¹³¹ In 1997, NASA's Mars Pathfinder Lander detected near its landing site several rocks who show percussion marks. Based upon other surface features on Mars, researchers assume that Mars was subjected to multiple flood episodes. Observations made during a

¹²⁸ A.J. JELINEK, B. BRADLEY, and B. HUCKELL: *The production of secondary multiple flakes*. *Am. Antiquity* **36**, No. 2, 198-200 (1971).

¹²⁹ J. EVANS: *The ancient stone implements, weapons and ornaments of Great Britain*. Longmans et al., London (1872), pp. 247-248.

¹³⁰ J.A.J. GOWLETT: *Tools – the palaeolithic record*. In: (S. JONES, S. BUNNEY, and R. DAWKINS, eds.) *The Cambridge encyclopedia of human evolution*. Cambridge University Press, Cambridge (1992), p. 350.

¹³¹ K.K.E. NEUENDORF ET AL. (eds.): *Glossary of geology*. American Geological Institute, Alexandria, VA (2005), p. 481.

flood in southern Iceland revealed that collision of rocks is audible and sounds like distant thunder.¹³²

- Percussion marks play a prominent role in interpreting early archaeological site formation and hominid behavior. Percussion marks are closely associated with hammerstone impact notches and show consistent micromorphological features which distinguish them from tooth marks and other classes of bone surface modification. Given indications of prehistoric hammer-stone breakage of marrow bones, an awareness of percussion marks is critical for accurately identifying the biological agents of bone modification at archaeological sites and provides a new diagnostic of carcass processing by hominids.¹³³

Percussion Force and Contact Time. Percussion forces of enormous magnitude can arise when “hard” bodies strike one another violently. However, they are only effective during the short duration when the striking bodies are in direct contact with each other. This *contact time* is typically composed of a *compression period* and a *restitution period* (⇒ Fig. 2.8). Contact times during percussion were first measured electrically by the British engineer Robert SABINE (⇒ 1876), who revealed that they are of very short duration – somewhere in the microsecond regime – and dependent on the mass and initial velocities of the percussion partners, their hardness, and the angle of impact. Peter G. TAIT (⇒ 1892), a Scottish professor of physics and mathematics, devised a percussion machine that was very similar in construction to a guillotine. This machine permitted the first continuous recordings of contact times during percussion events. Using a graphical method, he also evaluated the duration of percussion for various practical examples, such as contact times between a golf ball and a club, one billiard ball with another, and a hammer with a nail.

It is interesting here to note that in the 18th century the concepts of percussion and impact were also applied on a merely theoretical basis to illuminate and prove the nature of motion and equilibrium. In the first part of his *Traité de dynamique* (Paris 1743), the French mathematician and encyclopedist Jean LE ROND D’ALEMBERT was inclined to reduce every mechanical situation to one of impact rather than to resort to the effects of continual forces. The U.S. historian

J. MORTON BRIGGS,¹³⁴ addressing this unique procedure in his biographical note, wrote, “D’ALEMBERT’s Third Law dealt with equilibrium, and amounted to the principle of the conservation of momentum in impact situations... His proof rested on the clear and simple case of two equal masses approaching each other with equal but opposite speeds. They will clearly balance one another, he declared, for there is no reason why one should overcome the other. Other impact situations were reduced to this one; in cases where the masses or velocities were unequal, the object with the greater quantity of motion (defined as $m v$) would prevail. In fact, D’ALEMBERT’s mathematical definition of mass was introduced implicitly here; he actually assumed the conservation of momentum and defined mass accordingly.”

Billiards. This game, which fascinates game players and laymen as well as physicists and mathematicians, became an important stimulus for percussion research {MARCI ⇒ 1639; HUYGENS¹³⁵ 1669}, because it allowed elastic collisions to be easily studied under almost ideal conditions. Its country of origin is unknown.¹³⁶ In the early days of the game, billiards players used a rather simple crooked stick, as shown in MARCI’s book on percussion entitled *De proportione motus...* (“On Proportions of Motion...”), which enabled the player to push rather than to strike the ball precisely {MARCI ⇒ 1639; ⇒ Figs. 4.3–A, B}. However, from 1735 onwards a straight tapered stick of polished wood, which was well balanced and fitted with an ivory reinforced tip – the “cue” –

¹³⁴ J. MORTON-BRIGGS: *Jean LE ROND D’ALEMBERT*. In: (C.C. GILLESPIE, ed.) *Dictionary of scientific biography*. Ch. Scribner’s Sons, New York, vol. 1 (1970), pp. 110–117.

¹³⁵ In a letter to Henry OLDENBURG, HUYGENS – then secretary of the Royal Society of London – solved the famous “carom” [French *carambolage*] problem of finding the point of reflection between two eccentrically colliding billiard balls by applying a hyperbola rather than a circle [See: *Œuvres complètes de Christiaan HUYGENS*, publiées par la Société Hollandaises des Sciences. Swets & Zeitlinger, Amsterdam; vol. 6 (1976): *Correspondence 1666–1669*, No. 1745; and HUYGENS’ letter to OLDENBURG (June 1669) on the *Problema Alhaseni*, p. 462].

¹³⁶ Some notes about the historical background of billiards might be useful to the reader. Its origin is obscure; its name is perhaps derived from the French word *billiard*, meaning a “stick.” There is reference to the game in SHAKESPEARE’s *Antony and Cleopatra* II, 5 (Cleopatra: “Let it alone, let’s to billiards,” written in 1606/1607), but the existence of billiards in pre-Christian times has not been substantiated. Encyclopedias such as the German *Meyer and Brockhaus* and the *Encyclopedia Americana* favor Italy as the country of origin, but the *Encyclopædia Britannica* also states that France, England, Spain and China have been credited with the invention of the game, and that the earliest references to the game in Europe occurred in the 15th century. The first concrete evidence of the existence of billiards traces back to France during the reign (1461–1483) of LOUIS XI, but its spread to other European countries did not start until 200 years later, during the unusually long reign of LOUIS XIV, covering the period 1643–1715 {⇒ Fig. 4.3–A}.

¹³² J.W. RICE JR.: *Flooding and ponding on Mars: field observations and insights from the polar realms of the Earth*. In: *Lunar & Planetary Science Conference XXXI*, Lunar & Planetary Institute, Houston, TX (2000), CD-ROM, Abstract No. 2067 (2000).

¹³³ R.J. BLUMENSCHINE and M.M. SELVAGGIO: *Percussion marks on bone surfaces as a new diagnostic of hominid behavior*. *Nature* **333**, 763–765 (June 23, 1988).

came into use. In a more advanced form of the game, the cue was turned into a precise, high-tech percussion tool. In the 18th century, Captain François MINGAUD, a French billiards champion, was the first to provide the cue with a leather tip.

John CARR, an English billiards teacher, invented the “side stroke” (1818), or “side” as it has come to be known; however, he had trouble with his glossy leather tip. In order to increase the adhesion between cue and ball, he was the first to use chalk, which he applied uniformly to the cue tip. This allowed him to impart a spinning motion to the cue ball by striking it off-center; striking the cue ball (a cue-tip width) above-center to impart overspin will cause the ball to roll forward, or to follow the object ball – the so-called “follow shot;” while striking it below-center will cause it to roll backward – known as a “draw shot.”¹³⁷ Striking the ball laterally off-center, which is called “side” in Great Britain, “English” in the United States, and *effet* in France, introduced new and amazing phenomena: striking the ball left and right of center causes the ball to spin clockwise and counterclockwise, respectively. On the other hand, striking the ball above and below the center increases and decreases the speed of the cue ball compared to normal speed, respectively.

These eccentric twists first illustrated the complex nature of percussion, particularly the influence of *spin*

- ▶ on the collision and reflection behavior of the cue ball after impact with an object ball or with the cushion;
- ▶ on the friction between a spinning ball and the cloth; and
- ▶ on the resulting velocity and direction of the struck ball.

These new phenomena stimulated the French engineer and mathematician Gustave-Gaspard DE CORIOLIS {⇒1835} to reflect on collision in the presence of friction and to develop the first mathematical theory of billiards, which he himself considered to be his best work. CORIOLIS, a professor at the Ecole Polytechnique who held the prestigious position of a *répétiteur*, was supported by General Henri A. DE THOLOZÉ, then director of this distinguished school and an ardent fan of billiards. He demonstrated various billiards *effet* phenomena to CORIOLIS, who analyzed them mathematically – resulting in a unique cooperation between a superior and a subordinate. His studies, laid down in his book *Théorie mathématique des effets du jeu de billard* (Paris 1835), also resulted in an important by-product – the discovery of the “Coriolis force.”

Ballistic Pendulum. The application of the Laws of the Conservation of Momentum and Energy, one of the basic

findings of 17th-century percussion research, resulted in a fundamental theory of impact and proved most useful in the *ballistic pendulum*. This simple but most ingenious instrument, first suggested by a French astronomer {CASSINI JR. ⇒1707}, was introduced into practical ballistics by the English mathematician and military engineer Benjamin ROBINS {⇒1740} in order to quantitatively determine the velocity of a moving bullet. The impulsive penetration of the bullet is so close to being instantaneous, and the inertia of the pendulum’s block is so large compared with the momentum of the shot, that the ball and the pendulum move as one mass before the pendulum has been sensibly deflected from the vertical. From θ , the angle of deflection, it is possible to calculate the impact velocity v_p of a musket or even of a cannon shot ($v_p \propto \sin \theta/2$). ROBINS also used the ballistic pendulum to study projectile drag as a function of its velocity, thus creating *aeroballistics* – an important branch of ballistics that deals with the aerodynamics of projectiles moving through the atmosphere; since World War II this field has also involved research on rockets and guided missiles, and on bombs dropped from aircraft.

ROBINS’ remarkable supersonic ballistic experiments, which he performed with spherical projectiles traveling at velocities of up to about 1,670 Engl. ft/s (509 m/s, $M \approx 1.5$ at 20 °C), revealed that aerodynamic drag increases considerably when approaching the velocity of sound. These experiments were repeated in 1958 and analyzed with modern instrumentation by the U.S. aerodynamicist Sighard F. HOERNER, who proved that ROBINS must have reached supersonic velocities with his gun shots {ROBINS ⇒1746}. However, the ballistic pendulum – albeit based upon an impressively simple principle – produces a number of errors in measurement, and thus the data obtained from it must be carefully analyzed {CRANZ 1927, see ROBINS ⇒1740}.

Percussion has not become a branch of science of its own, but has instead acted as an important multidisciplinary tool (and it still does), thereby stimulating science and technology in a variety of ways and initiating new fields in applied physics. Examples include *shock wave physics* in general, and *solid-state shock wave physics* and *impact physics* in particular. In addition, applications of percussion phenomena and methods have created new disciplines of great economic significance, such as *impact engineering*, *dynamic materials testing*, *seismic surveying*, and *biomechanics*.

2.2.4 APPLICATIONS OF PERCUSSION

Applications of the principle of percussion in classical terms – i.e., the direct impact of one body against another – are as

¹³⁷ A *follow shot* is when the cue ball stops momentarily, then follows the object ball’s direction upon contact with the object ball. The *draw shot* makes the cue ball spin back after it impacts the object ball.

old as mankind itself and encompass most types of weapons and tools that have been invented. Percussion is used for special purposes in industry and science, and even in medicine. However, compared to the huge number of applications of shock waves, pure percussion techniques are limited to rather few applications. In modern science and engineering, the term *percussion* has been replaced almost entirely by the term *impact*, an important branch of dynamics covering a wide range of loading rates which is now treated in special textbooks {e.g., GOLDSMITH \Rightarrow 1960; KINSLOW \Rightarrow 1970}, journals [Int. J. Impact Engng. \Rightarrow 1983] and technical reports, and at symposia, conferences and workshops {e.g., Int. Symp. on Structural Crashworthiness \Rightarrow 1983; DYMAT \Rightarrow 1985; HVIS \Rightarrow 1986; SUSI \Rightarrow 1989; Int. Conf. on Large Meteorite Impacts and Planetary Evolution \Rightarrow 1992; ISIE \Rightarrow 1992; crashMAT \Rightarrow 2001}.

Pile Driving, Steam Hammer. The principle of percussion has been used since the earliest times for *pile driving* {Old World \Rightarrow c.10,000 B.C.}. Numerous tools and weapons based upon percussion were developed in antiquity, for example war galleys with rams on their bows, wall hammers, battering rams [Lat. *aries*], and catapults [Lat. *ballistae*] { \Rightarrow Figs. 4.2–F, G}. With the advent of pile engines {DA VINCI \Rightarrow 1490s; BESSON \Rightarrow 1578; GROLLIER DE SERVIÈRE \Rightarrow 1719; \Rightarrow Fig. 4.2–N}, the question of how to optimize their efficiency was discussed, and the influence of friction between the pile and the soil was recognized {HUTTON \Rightarrow 1812}.¹³⁸ The steam hammer, a British invention {NASMYTH \Rightarrow 1838} based on the principle of percussion, soon became an indispensable tool in most pile driving and drop forge techniques. The first huge drop forging presses were built and operated in the early 1890s, e.g., at the Bethlehem Iron Company in Pennsylvania (weight of the ram block: 113.4 tons, dropping height: 6 m), at Schneider & Co in Le Creusot, France (80 tons, 5 m), and at the Kruppwerke in Essen, Germany (50 tons, 3 m). These were important requirements for the evolution of the heavy industry, as well as proud national symbols of progress and unlimited technical feasibility. *Drop forging*, where the metal is hammered between two dies, also became an important mass production technique, although it is only suitable for producing small and medium size objects. The hammer is dropped from its maximum height, to which it is usually raised by steam or air pressure.

Percussion Drilling. This technique of sinking a borehole was invented by the German technician Karl G. KIND { \Rightarrow 1834; \Rightarrow Fig. 4.2–Q}, who used a tool that repeatedly dropped onto the same spot. This technique allowed the first deep-drilling of holes in rocks. The method stimulated the invention of the pneumatic drilling hammer, which proved its great utility during the construction of the 15-km-long St. Gotthard Tunnel (1872–1881) connecting Switzerland with Italy. Drilling hammers became indispensable tools in the construction industry, particularly when working heavy concrete. Today electric and pneumatic drilling hammers have become widespread tools for the professional as well as for the do-it-yourselfer.

A modern outgrowth of percussion drilling is *laser percussion drilling*, a more recent development. The term *percussion* refers to the repeated operation of the laser in short pulses (10^{-3} s), which are separated by longer time periods (10^{-2} s). The energy supplied by the laser is bounded, and pulse-wise behavior allows for large bursts of energy. The actual drilling predominantly consists of removal by melt ejection, a process initiated by the sudden expansion of the vapor evaporating from the surface heated by absorption of laser energy. The gas dynamics for this complex process is similar to the well-known model of a shock tube.¹³⁹

Crushing, Fragmentation. The understanding of percussion phenomena also provided new insights into traditional engineering applications, for example the mechanical processes of crushing and fragmentation of brittle materials, as used in the industrial treatment of stones and ores.¹⁴⁰ The *percussion grinder* is a machine for crushing quartz or other hard material by a combined rubbing and pounding process. The *wrecking ball*, a medieval technique, is still widely used to demolish concrete and masonry structures { \Rightarrow Fig. 4.2–P}. Suspended from a cable attached to a crane, the wrecking ball, which is usually a pear-shaped iron body that can weigh of up to 10 tons, is either dropped onto or swung into the structure that is to be demolished.

Fluid Jet Impact. The interaction between a moving solid body and a liquid jet emerging from a nozzle at high pressure can provoke the plastic deformation of the liquid jet or the brittle fracture of the jet, depending on the viscosity of the liquid and the impact velocity {KORNFELD \Rightarrow 1951; \Rightarrow Fig. 4.3–V}. This curious phenomenon has been explained by a relaxation mechanism {KOZYREV & SHAL'NEV

¹³⁸ Kinetic (or dynamic) friction occurs when two objects are moving relative to each other and rub together. The *coefficient of kinetic friction* depends on the pair of surfaces in contact (roughness) and on the sliding velocity; it is usually less than the *coefficient of static friction*.

¹³⁹ K. VERHOEVEN: *Modelling laser percussion drilling*. Proefschrift Technische Universiteit Eindhoven, The Netherlands (2004).

¹⁴⁰ H.H. GILDEMEISTER: *Spannungszustand und Bruchphänomene in prallbeanspruchten Kugeln*. Ph.D. thesis, Fakultät für Chemie-Ingenieurwesen der TH Karlsruhe (June 1976).

⇒1970; ⇒Fig. 4.3–W}. On the other hand, a characteristic peculiarity of the impacts of miniature volumes of fluid (drops, jets) onto a solid is the generation of a pressure peak in the fluid pressure-time profile acting on the solid. This pressure pulse can be regulated as desired by utilizing fluids with different relaxation times, changing their temperature, or by adding polymers.

Studying and understanding impact phenomena of a high-velocity liquid (water) jet on a solid surface {HEYMANN ⇒1969} are also important tasks when attempting to raise the efficiency of hydraulic equipment operated by liquid jet impact, such as in water jet cutting technology¹⁴¹ and hydraulic mining.¹⁴² The latter technique was one of the dominant processes used by the California gold mining industry and was in use from the mid-1850s until 1884. It involved dropping water almost vertically hundreds of feet down to the mining site and channeling it through heavy iron pipes, where it exploded from nozzles in so-called “water cannons,” thus disintegrating gold-laden banks of soft gravel and leaving huge craters.

Firearms. The principle of percussion has also been widely used in the construction of reliant firearms. The disadvantages of flintlocks became particularly obvious during the Napoleonic Wars (1803–1815). The inventions of the *percussion lock* {FORSYTH ⇒1805}, a system that used a small pill of detonating explosive (fulminating powder) placed below a plunger at the entrance to the touchhole, which overcame the disadvantages of the flintlock ignition, and the invention of the *percussion cap* (or *percussion primer*) {SHAW ⇒1815}, an outgrowth of FORSYTH’s idea {⇒1805}, created a wealth of new percussion-related terms, such as

- ▶ the *percussion arm* – usually a small-arms type weapon based on the detonation of an explosive when struck sharply;
- ▶ the *percussion bullet* (or *explosive bullet*) – a bullet containing a substance which is exploded by percussion;
- ▶ the *percussion fuse* – a fuse used in shells and case shots which ignite by the impact of the projectile striking the target;
- ▶ the *percussion gun* – the name given to firing a gun by means of a percussion cap placed over the flash hole;
- ▶ the *percussion lock* – the lock of a gun that is fired by percussion upon fulminating powder;

- ▶ the *percussion match* – a match which ignites by percussion; and
- ▶ the *percussion powder*, the powder used in percussion caps (since about 1832 consisting of mercury fulminate).

Percussion systems combining propellant, bullet and primer {DREYSE ⇒1827} eventually led to the modern cartridge, which revolutionized the science of war. To some extent the percussion cap can also be regarded as the archetype of the blasting cap, the so-called “detonator” {A. NOBEL ⇒1863/1864}.

Intense Sound Generation. In musical acoustics, the most intense percussion instruments are huge metal bells which are struck near the rim by a metal striker inside the bell or an exterior hammer. The acoustical structure of the sound of the bell is a complex mixture of partials that depends not only on the bell’s geometry but also on the metals used for the two percussion partners (bell and striker), and the locus of percussion.

Artificial seismic waves are also generated via the principle of percussion, such as by weight-dropping units, high explosives (“explosion seismology,” see Sect. 2.7.1) or by “vibrator trucks” where hydraulic pistons oscillate a mass in a vertical manner imparting a force through a base plate attached to the ground, thus inducing vibrations directed down into the earth. Pneumatic air-guns are also used, particularly in marine environments, which generate strong sound waves by releasing a burst of extremely high-pressured air into the water. So-called “seismic air-guns” usually operate at about 2,000 psi and typical volumes of air expelled vary from 30 in.³ (492 cm³) to about 800 in.³ (13,104 cm³).¹⁴³ Large air-gun arrays normally employed produce sound levels of 260–270 dB (re 1 μPa) at 1 m.

Medical Diagnostics. In medicine, percussion is used in physical diagnostics to obtain information about what lies below the skin (in physics, a similar procedure is used to determine the natural frequencies of a body by striking it with a hammer). Although it is a rather ancient method {VON AUENBRUGGER ⇒1754}, it is still routinely used in chest and abdomen diagnostics: the clinician strikes the skin with a finger or a hammer, setting up vibrations; the resulting sounds are then interpreted. If the stroke is made upon the body, it is called “immediate percussion;” if upon something placed against the body (e.g., a finger of the other hand, or a small instrument made for this purpose), “mediate percussion.”

¹⁴¹ F. HAMMELMANN (1997), see LEACH & WALKER {⇒1965}.

¹⁴² D.A. SUMMERS: *Hydraulic mining: jet assisted cutting*. In: (H.L. HARTMAN, ed.) *SME (Society of Mining Engineers) handbook*. Society of Mining, Metallurgy and Exploration, Littleton, CO (1992), chap. 2.2.3.

¹⁴³ W. DRAGOSET: *A brief overview of seismic air-gun arrays*. The Leading Edge 19, No. 8, 898–902 (Aug. 2000).

Biomechanics. By definition, *biomechanics* is the analysis of the mechanics of living organisms and their parts, which makes use of the laws of physics and engineering concepts to describe the motion of body segments, and the effects of internal and external forces which act upon them during movement and rest. A particular branch of this discipline is the study of the response of muscles, joints, bones and other parts of the human body to the sudden application of forces resulting from a single blow or repetitive blows, and from interactions with shock waves. The subject has gained increasing attention from not only the military, industry and those working in sport, but also by insurance companies and courts. Examples of shock-type biodynamics addressed in this book include:

- ▶ skull injuries caused by percussion {MARCI \Rightarrow 1639};
- ▶ explosion-like injuries in soft tissue resulting from projectile impact {MELSENS \Rightarrow 1872};
- ▶ injuries to the cerebral spine and its tissues caused by sudden forceful flexion or extension to the neck – so-called “whiplash” {CROW \Rightarrow 1928};
- ▶ severe injuries like swelling of the brain, hemorrhaging, and neck injuries that result when a baby (or child) is shaken – so-called “shaken baby syndrome” {GOLDSMITH \Rightarrow 1960};
- ▶ injuries to the muscles and tendons of the outside of the elbow that result from overuse or repetitive stress in the application of hand-held percussion tools and certain sports equipment – such as “tennis elbow” and “golfers elbow” {BRODY \Rightarrow 1979; HATZE \Rightarrow 1998};
- ▶ the intense hammering shock that should be experienced by the brain of a woodpecker but which is, in fact, heavily reduced by internal protection mechanisms {BECHER \Rightarrow 1953};
- ▶ human injuries caused by strong blast waves resulting from guns and explosions (*see* Sect. 2.1.5); and
- ▶ injuries to marine animals caused by the impact of underwater shock waves resulting from underwater detonations {LEWIS \Rightarrow 1996}.

Biomechanics even touches upon such daily activities as walking and running: during each step, a rapid deceleration occurs at the foot/ground interface, resulting in a shock being imparted to the musculoskeletal system, and insufficient shock attenuation may result in severe overuse injuries. This has brought up the important question of how footwear can be designed to attenuate the *foot/ground impact shock*, and how such properties can be tested.¹⁴⁴

¹⁴⁴ This problem has been discussed and studied by numerous biomechanics researchers; *see*, for example, the review paper by Joseph HAMILL, a biomechanics professor at the University of Massachusetts, Amherst, MA, entitled *Evaluation of Shock Attenuation*, which he presented at the 4th

2.3 EARLY SPECULATIONS ON SUPERSONIC PHENOMENA

*The unprecedented identification of the spectrum of an apparently stellar object [quasar 3C 273] in terms of a large red-shift suggests either of the two following explanations. (i) The stellar object is a star with a large gravitational red-shift. Its radius would then be of the order of 10 km... (ii) The stellar object is the nuclear region of a galaxy with a cosmological red-shift of 0.158, corresponding to an apparent velocity of 47,400 km/sec.*¹⁴⁵

Maarten SCHMIDT
Mt. Wilson and Palomar Observatories
Southern California 1963

HIGH-SPEED natural phenomena have aroused the curiosity as well as the anxiety of man from the earliest times. With the evolution of fluid dynamics and thermodynamics beginning in the 19th century, the causes of most terrestrial high-rate phenomena have been understood using scientific methods and improved instrumentation. Furthermore, with the progress in radiation and nuclear physics in the 20th century many solar phenomena have been understood as well.

With the rapid development of astronomical diagnostics in the last 50 years and the increasing use of space probes, it became possible to observe celestial objects and cosmical nonstationary phenomena up to remote distances of the Universe. However, numerous phenomena, having enormous velocities of recession ranging from a few percent up to nearly the velocity of light and associated with shock waves, are still a mystery to modern science – such as the nature of quasars, the fluid dynamics of astrophysical jets and supermassive black holes, and the origin of cosmic rays and gamma-ray bursts. Science has now reached a higher level of understanding cosmic phenomena but at the same time also produced more complex questions and new riddles.

Compared to terrestrial natural violent events – perceived by a remote observer after delay times ranging from milli-

Symposium of the Technical Group on Footwear Biomechanics [Canmore, Canada, Aug. 1999].

¹⁴⁵ M. SCHMIDT: 3C 273: *a starlike object with large red-shift*. *Nature* **197**, 1040 (1963). He reached the conclusion that the quasar 3C 273 was not a star, but the enormously bright nucleus of a distant galaxy. • Quasars are extremely distant celestial objects whose power output is several 1,000 times that of our entire galaxy. His discovery that their spectra have a large red shift revolutionized quasar research. Subsequently, the radio source 3C 48 was found to have a redshift corresponding to a velocity of recession of 37% the speed of light. Strong evidence now exists that a quasar is produced by gas falling into a supermassive black hole in the center of a galaxy. • Estimations of these enormous velocities are based on the assumption that the red shifts are *cosmological*, which implies that the objects have to be billions of light-years away and therefore extremely luminous to look as bright as they do in our night sky.

seconds/seconds (thunder), to seconds/minutes (seismic shocks, blasts from explosive volcanic eruptions) up to minutes/hours (tsunamis) – the electromagnetic waves, originating from remote violent cosmic events and received by optical, radio or X-ray telescopes, have traveled millions to billions of light-years until arriving at a terrestrial observer. This implies that astrophysical diagnostics can only provide a picture of the cosmical past: current events at remote distances in the Universe are not accessible by any diagnostics, only by computational simulation. Furthermore, it is well-known from the study of terrestrial chemical and nuclear detonations that their durations as well as their effects at remote distances increase with increasing yield. Cosmic detonations have enormous yields and consequently their effects can last hundreds to thousands of years. For example, the famous Crab Nebula is a remnant of the supernova SN 1054 which astronomers had witnessed in A.D. 1054. The “detonation products” of this event, a cloud of hot ionized gases creating the 11-light-years-diameter Crab Nebula, are still expanding into the cold gases (now at a rate of 1,500 km/s), thereby producing shock waves.

The most common high-rate terrestrial phenomenon is thunder and attempts to understand this phenomenon promoted the evolution of supersonics.¹⁴⁶ However, before we begin to discuss this fascinating pioneering phase which took place in the 19th century, it first seems worthwhile to look back to the very beginning of supersonics. Its roots reach back as far as to the 1630s, when percussion research was still in its infancy and ballistics was limited to empirical testing only. Some unique highlights on the road towards supersonics are illustrated as cartoons in Fig. 2.10.

In the 1630s, the French clergyman, natural philosopher and mathematician Marin MERSENNE first determined the velocity of sound in air by firing a cannon and observing the delay between the arrivals of the muzzle flash and the muzzle blast a large distance away {MERSENNE \Rightarrow 1636; \Rightarrow Fig. 2.10–A}. He correctly assumed that the velocity of light is extremely large compared to the velocity of sound, which we know to be true today but was then a much more controversial assumption then, and one that resulted from much debate. Using his so-called “flash-to-bang rule,” he also proposed to evaluate the distance of a lightning strike.¹⁴⁷ Later, this method was also used to determine the velocity of sound in water {COLLADON \Rightarrow 1826}.

In the early 1640s, MERSENNE resumed his ballistic studies and considered how he might determine the velocity of a musket ball. When positioning himself close to the target, he noticed that the impact of the ball was heard at almost the same time as the muzzle flash {MERSENNE \Rightarrow 1644; \Rightarrow Fig. 2.10–B}. From this he concluded that the ball must propagate with a velocity close to that of sound. Since the muzzle blast of a musket initially propagates at supersonic velocities, and even the speed of the ball fired from a musket, as first measured one hundred years later by Benjamin ROBINS using the ballistic pendulum {ROBINS \Rightarrow 1740; \Rightarrow Fig. 2.10–C}, can be supersonic, it is quite possible that he had already experimented with supersonics – but without knowing it.

Based on this very simple though ingenious method of comparison, we can place MERSENNE at the front line of early sonic – perhaps even supersonic – pioneers. His idea of comparing a rapid phenomenon of unknown velocity with another one of known velocity reduces the problem, such that the ear only has to evaluate whether there is a time delay between two events.¹⁴⁸ In the Great Lisbon Earthquake { \Rightarrow 1755}, it was observed that the velocity with which the quake and its aftershocks were propagated “was the same, being at least equal to that of sound; for all followed immediately after the noise that preceded them, or rather the noise and the earthquake came together” {MICHELL \Rightarrow 1760}, thus providing a first quantitative estimate of the velocity of propagation of seismic shocks.

In the 19th century, MERSENNE’s method of comparison played an important role in the genesis of shock wave physics, serving as an experimental proof of the first mathematical theory of shock waves {EARNSHAW \Rightarrow 1860}: the British naval officers and arctic explorers Sir William E. PARRY, Henry FOSTER and Sir John ROSS { \Rightarrow 1824/1825}, who were searching for the Northwest Passage, observed that at a fairly large distance from a gun the officer’s word of command “Fire” was distinctly heard *after* the report of the gun { \Rightarrow Fig. 2.10–D}. This proved in a unique way that the muzzle flash, a weak shock wave, propagates faster than sound.

velocity of sound in a solid in this way on a laboratory scale requires advanced instrumentation, which was not available to 19th-century physicists. The easier *indirect method* ($c = \lambda \nu$), which only requires a Kundt tube (A. KUNDT 1866) and a tuning fork, was instead used to obtain the first data on the velocities of sound in solids. However, since this method only works with standing acoustic waves, it is not applicable to shock waves.

¹⁴⁸ The temporal resolution of the ear is about 2 ms, while the just-noticeable interaural delay ranges between 30 and 200 μ s. See E. ZWICKER and H. FASTL: *Psychoacoustics: facts and models*. Springer, Berlin etc. (1990), p. 262.

¹⁴⁶ In the 1950s, the term *supersonics* was also applied in physical acoustics to the study of high-frequency sounds, above-audio frequencies – a branch of acoustics now termed *ultrasonics*.

¹⁴⁷ MERSENNE’s method for determining the sound velocity c is the oldest one known and is now termed the *direct method* ($c = \Delta s / \Delta t$). To determine the

2.3.1 OBSERVATIONS IN NATURE: STIMULATING RIDDLES

*I strongly suspect it will soon be established as a law of nature, that the sound of a thunder-clap is propagated with far greater rapidity than ordinary sounds.*¹⁴⁹

The Rev. Samuel EARNSHAW
Church and Parish of Sheffield 1860

*ABBE's theory reminds one of the explanations of detonation given by JOURNÉE, SEBERT, DE LABOURET, in a certain way, regarding the concentration of noise, also of BOSSCHA's hypothesis. However, nowhere does ABBÉ speak of a head wave which the meteorite, moving at large speed, is carrying with it, and which, according to our explanation, is the primary cause of the main detonation heard during a meteorite fall. Since this view has been expressed, further observations have been made which further confirm the correctness of this widely supported theory.*¹⁵⁰

Ernst MACH
Karl-Ferdinand-Universität
Prague 1893

Shock waves are a common natural phenomenon on Earth. They are produced in the form of blast waves in the near-field of a thunderclap and during the fall of meteorites. Under certain conditions they can also arise during phreatic (or explosive) eruptions of volcanoes, for example when water and heated volcanic rocks interact to produce a violent expulsion of steam and pulverized rocks. Earthquakes and volcanic eruptions can generate seismic shocks and tsunamis, capable of producing disastrous effects also in remote areas. Asteroids, rocky “mini planets” moving in orbit around the Sun and ranging in size from about 1 to 1,000 km, can produce the most massive terrestrial shock effects when they impact the Earth, resulting in global catastrophes with biological mass extinctions. In the following, these natural supersonic phenomena will be illuminated in more detail.

Thunder. In prehistoric times, thunder was regarded as a deity and in antiquity it was worshipped by various nations {⇒Fig. 4.1–J}. Thunder is probably the most common of all loud natural sounds. Calculations performed in the 1920s estimated that there were several thousand lightning flashes per hour around the world. However, in spite of improved diagnostics, exact data on this are still difficult to obtain, because many lightning discharges occur between clouds, which may not be detectable, even with modern satellite

surveillance. Since thunder also plays an important role in the evolution of shock physics, it appears useful to address this striking phenomenon more specifically.

Early naturalists were fascinated by thunder and proposed somewhat curious hypotheses about its origin {ARISTOTLE ⇒333 B.C.; SENECA ⇒A.D. 63; DESCARTES ⇒1637; MERSENNE ⇒1644; MARIOTTE ⇒1673; LÉMERY ⇒1700; WALL ⇒1708; FRANKLIN ⇒1749; ARAGO ⇒1838}. Upon applying the flash-to-bang method {MERSENNE ⇒1636}, some French scholars {MONTIGNY ET AL. ⇒1860; LAURENT 1860; HIRN ⇒1860} estimated unrealistically high propagation velocities of thunder, ranging from the velocity of sound in air to extreme values of above 6,000 m/s. The Rev. Samuel EARNSHAW {⇒1851}, an English mathematician, performed key work due to his experiences with lightning and thunder {⇒Fig. 2.10–E}. His conclusions – though partly incorrect from a modern perspective – stimulated him to such a degree that he worked out the first mathematical solution to POISSON's crude concept {POISSON ⇒1808} of treating sounds of finite amplitude {EARNSHAW ⇒1860}.

Today thunder is not only of interest to atmospheric acousticians due to its relevance to atmospheric properties, but it has also prompted modern shock and plasma physicists to develop numerical models that describe the complex generation and propagation of the shock wave from a rapidly heated and expanding discharge channel. Since the 1970s, a considerable number of experimental and theoretical research papers dealing with the generation of thunder have been published which, partly based on reproducible laboratory conditions, have been able to explain some of the many puzzling phenomena. More recently, various review articles have been published on this complex subject.^{151, 152, 153}

In spite of the many theories on the cause of thunder proposed in recent years and the progress made in understanding this complex phenomenon, it is still a scientific riddle and remains a challenge to theoreticians as well as experimentalists. For example, Peter GRANEAU, a U.S. physicist at the Northeastern University in Boston, speculated that thunder may not be caused by the thermal expansion of the lightning channel, but may instead be driven by the sudden liberation of chemical bond energy from the nitrogen and oxygen molecules of the air {GRANEAU ⇒1989}.

¹⁵¹ A.A. FEW JR.: *Acoustic radiation from lightning*. In: (E.P. KRIDER, ed.) *The Earth's electrical environment*. National Academy, Washington, DC (1986), pp. 46–60.

¹⁵² M.A. UMAN: *All about lightning*. Dover Publ., New York (1986); *Lightning*. In: (R.G. LERNER and G.L. TRIGG, eds.) *Encyclopedia of physics*. VCH, New York etc. (1991), pp. 637–639.

¹⁵³ H.E. BASS: *Atmospheric acoustics*. In: (G.L. TRIGG, ed.) *Encyclopedia of applied physics*. VCH, New York etc.; vol. 2 (1991), pp. 145–179.

¹⁴⁹ See EARNSHAW {⇒1860}.

¹⁵⁰ See E. MACH & DOSS {⇒1893}.

Modern theories of chemical evolution suggest that the early Earth was covered largely with a warm, slightly alkaline ocean. In 1953, Stanley MILLER, a graduate student working with Nobel Prize winner Dr. Harold UREY, published experiments on the synthesis of amino acids in a simulated primordial Earth environment using electric sparks. The *Miller-Urey experiment*, an experiment that produced an “organic soup,” became a landmark in chemical evolution {S.L. MILLER \Rightarrow 1953; \Rightarrow Fig. 4.14–A}. Similar experiments were later carried out using high-temperature shock waves generated in a shock tube { \Rightarrow Fig. 4.14–B}. George T. JAVOR,¹⁵⁴ an associate professor of microbiology at the Loma Linda University in California, who discussed modern views on the origin of life in 1987, wrote: “Though rich in carbon monoxide, carbon dioxide, ammonia, methane, hydrogen, and nitrogen, the atmosphere [of the early Earth] definitely did not contain atomic or molecular oxygen. Ultraviolet light from the Sun, geothermal energy from volcanoes, shock waves from thunder, and cosmic radiation acted upon gases of the primitive atmosphere causing the formation of biomonomers such as amino acids, sugars, purines, pyrimidines, and fatty acids. These substances polymerized to form the prototypes of more recent proteins, nucleic acids and cell membranes. In time they coalesced to form the first proto-cell, a collection of polymers enclosed in a membrane. Eventually these protocells became increasingly complex, until the first true living cell was born.”

Thunder has a very complicated acoustic structure, because it is the result of lightning, itself a complex phenomenon. It is difficult to realistically simulate thunder in a laboratory. For example, Guy G. GOYER { \Rightarrow 1964/1965}, a research physicist at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, used a long detonation cord (“Primacord”) with a specific charge weight of 12 grams of PETN per meter, a value which he obtained based on theoretical calculations of the shock wave generated by lightning. However, the detonation of the Primacord does not occur at all points simultaneously, but rather represents a point source propagating with the velocity of the detonating PETN cord. A line source closely approaching the characteristics of lightning can only be realized by using long spark channels, which require the use of very high voltages. Laboratory experiments on lightning and measurements of the shock pressures generated were conducted by Martin A. UMAN { \Rightarrow 1970} at Westinghouse Research Laboratories, while Henry E. BASS { \Rightarrow 1980}, a physics professor at the University of Mississippi, performed various numerical simulations. These stud-

ies have indeed shown that the disturbance starts out as a shock wave in the close vicinity of the stroke. However, just a few yards from the channel, the shock wave quickly turns into a weak shock wave – *i.e.*, it propagates at almost the velocity of sound, thus confirming the long-known rule of thumb {MERSENNE \Rightarrow 1636} that the distance of the nearest flash of lightning from the observer can be estimated by measuring the time lag between the flash and thunderclap.

The source of most lightning is the electric charge separation that occurs in a thunderstorm, although other forms of lightning can occur, *e.g.*, due to charge separation in snow- and sandstorms, in the clouds generated by some volcanoes, and near thermonuclear explosions. Most lightning flashes produced by thunderstorms are intracloud discharges, but cloud-to-ground lightning – also known as “streaked lightning” – has been studied more than any other form of lightning because of its practical interest and (relative) ease of observation. The discharge channel, which rapidly ionizes, heats and expands the gas along its path, can reach a length of a few kilometers and a diameter of up to a few centimeters, thereby typically carrying a current of some 10 kA and dissipating an energy of about 3 kJ per meter.

The development of the shock from this rapidly expanding channel can be calculated using *weak shock theory* {WHITHAM \Rightarrow 1956 & 1974}. Since the strike has a finite length, the shock wave is primarily cylindrical close to the spark, but becomes increasingly spherical at long distances from the spark. However, in real lightning the discharge channel has a tortuous geometry, giving rise to a “string of pearls,” which means that thunder must be modeled as a long line of spherically spreading sources – *i.e.*, the solution represents a complex combination of the classical examples of a “point source” explosion {G.I. TAYLOR \Rightarrow 1941} and a “line source” explosion {LIN \Rightarrow 1954}.

The sharp report that can be heard from a thunderclap – which strongly resembles the muzzle blast of a rifle, a shock wave – is only heard when lightning strikes nearby. At larger distances, however, the sound of thunder is modified during its propagation by nonlinear effects in the atmosphere and ground effects that shift the spectrum to lower frequencies, giving rise to the low-frequency rumbling typically heard. In addition, the cloud-to-ground discharges, which are best investigated using high-speed diagnostics, show a rapid sequence involving a moving stepped leader which initially descends from the cloud to the ground and then returns to the cloud; 10 to 20 strikes following this first one then follow. The first return strike of the lightning flash produces a much louder sound than the leader, because it transmits a more powerful electric current. In his work on thunder, the

¹⁵⁴ G.T. JAVOR: *Origin of life: a look at late 20th-century thinking*. Origins 14, No. 1, 7-20 (1987).

Rev. Samuel EARNSHAW {⇒1851 & 1858} observed that a lightning stroke – obviously belonging to this particular type of cloud-to-ground discharge – was heard in the village *almost simultaneously* with the flash although the lightning struck about a mile outside of the village. From this observation, he used the flash-to-bang method to estimate the propagation velocity of thunder, which he found to be supersonic. However, he may have erroneously taken the sequence of rapid flashes and strikes to be a single event.

The loudest natural sounds in the ocean are lightning strikes, with a source level of about 260 dB (re 1 μ Pa). Strikes occur at a rate of about two per km² per year in most of the world's coastal regions, where coincidentally marine mammals abound.¹⁵⁵

Lightning is not unique to Earth. In 1979, cameras on NASA's Voyager 1 planetary explorer spacecraft found lightning on Jupiter.¹⁵⁶ Both Voyager 1 and 2 detected electrical signals from Jupiter characteristic of lightning. This discovery was the first hard evidence that such violent electrical discharges take place on other planets. In 1997, the Galileo spacecraft also photographed what appear to be visible lightning flashes in Jupiter's turbulent atmosphere {RINNERT ⇒1985}. Detection of electrostatic discharges on Saturn and Uranus by Voyager 2, along with radio signals associated with lightning picked up by the Pioneer Venus orbiter and the Russian Venera probe, may indicate that lightning – most probably also accompanied by violent thunderclaps; i.e., by weak atmospheric shock waves – are commonplace on some planets in our Solar System.

Hydrometeors. The generic term *hydrometeor* is used to designate all products of the condensation or sublimation of atmospheric water – e.g., rain drops, ice crystals, fog, hail, and clouds. The physical constitutions of hydrometeors can actually be modified by acoustic waves of finite amplitude. In the Middle Ages, church bells were often rung in the hope of reducing the damage due to heavy storms. In the 1890s, experiments were carried out in Texas aimed at producing artificial rain by firing explosive charges on the ground or at an altitude of several thousand feet {DYRENFORTH ⇒1891}. During the First and Second World Wars, several reports indicated the occurrence of heavy rain immediately after ferocious artillery battles. Explosive charges have been used since the 1950s in various European countries and in South

Africa to generate shock waves in clouds in an effort to reduce crop damage from hail. Roland IVES {⇒1941}, a U.S. meteorologist, noticed that the firing of a revolver triggers super-cooled fog droplets to become frozen {MAURIN & MÉDARD ⇒1947}. Guy GOYER {⇒1964/1965}, a U.S. research physicist, detonated a long detonation cord (a “Primacord”) 300 ft above the cone of the Old Faithful Geyser at Yellowstone Park and observed that hail fell immediately following the detonation. He also reported on previous speculations that lightning, which acts as a shockwave generator, can affect hailstones, supercooled water droplets, and large cloud droplets.

As the velocities at which aircraft travel have increased, the problem of rain erosion has become more and more obvious. In 1945, U.S. Air Force personnel reported on observations of rain erosion phenomena in plastic materials {U.S. Air Force ⇒1945}. With the advent of supersonic flight {YEAGER ⇒1947} and of hypersonic flight {X-15 ⇒1961}, this serious problem became an urgent research topic, focusing particularly on the interaction of the head wave – a weak shock wave – with rain droplets, and the disintegration process itself {HANSON ET AL. ⇒1963; The Royal Society ⇒1965; BOWDEN & MCONIE ⇒1965; BRUNTON & BOWDEN ⇒1965}.

Bores. Since bores are primarily caused by tides – i.e., by the gravitational forces exerted by the Moon and the Sun – they are also appropriately termed *tidal bores*. Bores are surface waves that propagate in shallow water with a steep, almost discontinuous front similar to a shock wave in air. In particular, when the Earth is aligned with the Sun and the Moon (a phenomenon known as “syzygy”), tides of maximum range, so-called “spring tides,” result {WANG CH'UNG ⇒A.D. 85}. In his account on the invasion of Britain, the famous Roman dictator Julius CAESAR¹⁵⁷ alluded to the nature of spring tides [Lat. *maritime aestus maximi*] as being perfectly well understood in connection with the phases of the Moon. Bores of significant height – described as a “wall of water” by observers – are generated either by the rushing of the tide up a narrowing estuary or by the collision and oblique interaction of two tides. The latter form, representing the oldest known natural phenomenon of nonlinear wave superposition {⇒Fig. 4.1–M}, can be followed by the naked eye and must have been noted by coastal dwellers long ago.

Bores can be observed in the rivers of many countries, such as the *barre* of the Seine, the *mascaret* (or *raz de marée*) of the Gironde, and the *pororoca* of the Amazon. a large amount of literature exists on some of the major bores,

¹⁵⁵ Where lightning strikes. Science@NASA (Dec. 5, 2001); <http://science.nasa.gov/headlines/y2001/ast05dec%5F1.htm>.

¹⁵⁶ D.A. GURNETT, R.R. SHAW, R.R. ANDERSON, and W.S. KURTH: *Whistlers observed by Voyager 1 – detection of lightning on Jupiter*. Geophys. Res. Lett. 6, 511–514 (June 1979).

¹⁵⁷ G.I. CAESAR: *De bello gallico*. Liber IV, 29 (55 B.C.).

while information on others is lacking, and evidence rests purely on observation. The Tidal Bore Research Society compiled a catalog of bores around the world, which (as of May 2006) encompassed 55 bores.¹⁵⁸

Large bores have been recorded in the Ganges and Amazon with heights of up to 5–6 m. However, the highest waves have been observed in China in the estuary of the Qiantang River, with heights of up to 8 m {⇒Fig. 4.1–L}. Tide-watching at the Qiantang River near Hangzhou, a town about 170 km southwest of Shanghai, has been performed for over 2,000 years: each year, on the 18th day of the 8th month of the Chinese Lunar Calendar (*i.e.*, near the time of the Autumnal Equinox), thousands of tourists make their way to the China International Qiantang River Tidal Bore Festival to watch this spectacular event. In England, the bore on the River Severn is certainly the best known example of this phenomenon, and the one that has been studied the most and for the longest as well {⇒Fig. 4.4–E}.¹⁵⁹ The *Severn bore* is produced by a tide that rises about 18 feet (5.5 m) in an hour and a half. This body of water becomes compressed in the narrowing funnel-shaped estuary, and heaped up into an advancing wave extending from bank to bank. Measurements carried out in 1849 by Captain F.W. BEECHEY had revealed that the Severn bore can reach heights up to 1.5 m and propagate with a velocity of about 12.5 mph (20 km/h); *i.e.*, it moves about four times faster than walking speed.¹⁶⁰

In Germany, tidal bores are appropriately called “jump waves” [Germ. *Sprungwellen*]. Since the height of the water behind the wave front is greater than that ahead of the front and the propagation velocity V increases with the water depth d according to the relation $V \propto d^{1/2}$ {DE LAGRANGE ⇒1781; BELANGER ⇒1828}, the front must propagate “supersonically” compared to the water at rest ahead. An approaching bore does not produce a report like the sonic boom of a supersonically moving body; it instead announces itself to the observer through an increasingly loud roaring sound. However, it is this discontinuous nature of the wave itself and its close mathematical analogy to a gaseous shock wave which attracted the curiosity of many early naturalists and stimulated the interest of modern physicists and mathematicians in nonlinear wave phenomena {JOUQUET ⇒1920; PREISWERK ⇒1938; H.A. EINSTEIN ET AL. ⇒1946/1947; GILMORE ET AL. ⇒1950}.

A bore can be intensified considerably by reflection; for example, by forcing it to striking a rigid obstacle at an angle which produces an enormous impulsive force on it. From a mathematical point of view, bores are like nonlinear shock wave phenomena. Similar to the oblique reflection of a shock wave, which more than doubles the pressure behind the reflected wave, the height of a bore can be more than doubled when it strikes a rigid wall obliquely.¹⁶¹ Depending on the angle of incidence, this can result in irregular reflection, creating a Mach stem {⇒Fig. 4.13–A}.

Tsunamis. Tsunamis are catastrophic seismic sea waves and are mainly a Pacific phenomenon {Komaishi Seaquake ⇒1896; Myojin-sho Reef Eruption ⇒1952}: they are rare in the Atlantic Oceans. In the Indian Ocean, the denser oceanic Indian plate subducts beneath the overriding continental Burma plate, which resulted very recently in the most destructive tsunami in recorded history. It devastated the coastal areas of several countries and killed almost 230,000 people from many nations {Sumatra-Andaman Islands Earthquake ⇒2004; ⇒Fig. 4.1–S}.

While tidal bores are recurrent events – *i.e.*, they are predictable and confined to estuaries and so are of only limited danger – tsunamis are (like earth- and seaquakes) unpredictable events, in both time and magnitude. Because of their suddenness and enormous destructive power, even at remote coasts, tsunamis were the subject of much discussion among early natural philosophers {MARCELLINUS ⇒A.D. 365; KANT ⇒1756; MICHELL ⇒1760} as well as among early seismologists {MALLET ⇒1846; RUDOLPH ⇒1887; ROTTOK ⇒1890; MILNE ⇒1898; Count BERNARD ⇒1907}. Modern research has revealed that the origins of tsunamis are quite complex.¹⁶² Tsunamis can be generated

- ▶ by impulsive large *vertical* tectonic displacements of the sea floor, which may reach five meters or more, resulting in (shallow) earthquakes in *subduction zones* with epicenters close to the coast, particularly when the earthquakes have large amplitudes and shallow foci ranging from 0 to 40 km – such as those resulting from the slippage of denser oceanic plates beneath continental plates {Aegean Earthquake ⇒365; Lisbon

¹⁵⁸ Documenting the worldwide tidal bore phenomena. Tidal Bore Research Society (TBRS); <http://tidal-bore.tripod.com/catalogue.html>.

¹⁵⁹ F. ROWBOTHAM: *The Severn bore*. Dawlish MacDonald, London (1964).

¹⁶⁰ R.A.R. TRICKER: *Bores, breakers, waves and wakes*. Am. Elsevier, New York (1965), p. 38.

¹⁶¹ Reflection intensification effects for the Qiantang bore {⇒Fig. 4.1–L} are illustrated in the book by John E. SIMPSON: *Gravity currents in the environment and the laboratory* [Cambridge University Press, Cambridge (1997), pp. 98–99].

¹⁶² K. IIDA: *Magnitude, energy, and generation mechanisms of tsunamis and a catalogue of earthquakes associated with tsunamis*. In: (D.C. COX, ed.) *Proc. Tsunami Meeting* [University of Hawaii, Honolulu, HI, 1961]. Union Géodésique et Géophysique Internationale, Monographie No. 24, L'Institut Géographique National, Paris (1963), pp. 7–18.

- Earthquake \Rightarrow 1755; Chilean Earthquake \Rightarrow 1960; Sumatra-Andaman Islands Earthquake \Rightarrow 2004}. On the contrary, *horizontal* tectonic displacements may reach twenty meters or more, but cannot produce tsunamis;
- ▶ by rapid injection of large masses of material into the ocean by violent volcanic eruptions {Santorin Volcano \Rightarrow 1645 B.C.; Krakatau \Rightarrow 1883; Myojin-sho Reef Eruption \Rightarrow 1952};
 - ▶ by earthquake-induced submarine landslides {Coast of Yorkshire \Rightarrow 1856};
 - ▶ by earthquake-induced coastal landslides {Lituya Bay \Rightarrow 1958; \Rightarrow Fig. 4.1-Q};
 - ▶ through the decomposition of a gas hydrate (a solid compound containing natural gas and water) at the shelf;¹⁶³
 - ▶ by impact of large objects from outer space such as meteorites, asteroids, *etc.*, into the sea {Chicxulub Crater \Rightarrow c.65 Ma ago}; and
 - ▶ by underwater explosions of nuclear devices {Test BAKER \Rightarrow 1946}.

Subduction is the commonest mechanism of tsunami generation. It represents a “line” source that produces rapid displacement of a long but comparatively narrow vertical water column which extends from the surface to the seafloor, can extend over hundreds of kilometers in length, and can therefore result in very destructive tsunamis. Shores located in the vicinity of and facing such line sources are particularly endangered by tsunamis, as has been demonstrated recently by the Sumatra-Andaman Islands Earthquake { \Rightarrow 2004}, which devastated the west coast of Sumatra in particular.

The other mechanisms listed above are limited to comparably small dimensions, and thus approach “point” sources which result in tsunamis of a smaller magnitude. Tsunamis are less frequent along Atlantic coastlines than in Asia-Pacific ones, but are still a danger; the only subduction zones around the Atlantic are the Puerto Rico Trench and the Antilles subduction zone around the eastern Caribbean, and the South Sandwich Trench south of South America.

The *characteristics of tsunamis* differ distinctively from wind-generated surface waves. In contrast to surface waves, the entire water column, from the surface to the seafloor, begins to move and transfer energy. In deep water, the wavelengths (the distance from crest to crest) are enormous, about 100–200 km, but the wave heights (or amplitudes) are small, only 0.3–0.6 m; thus, in the open ocean on board a ship, a tsunami is barely noticeable. The resulting wave steepness, or ratio of height to length, is on the order of only 10^{-6} .

Since the waves have long periods of an hour or more, the corresponding rise times are on the order of many minutes – *i.e.*, extremely long compared to rise times in shock waves, which are on the order of nano- to microseconds. Since tsunami wavelengths are much longer than even the greatest ocean depths, they behave as *shallow water waves*, regardless of the depth H , and their velocity v can be described by the simple relation $v = (gH)^{1/2}$, where g is the acceleration due to gravity {DE LAGRANGE \Rightarrow 1781}.¹⁶⁴ This formula was used in the 19th century by geologists to determine the average depths of the oceans, long before deep-sea soundings were taken {Arica Earthquake \Rightarrow 1868; Iquique Earthquake \Rightarrow 1877}. In addition, the relationship also has enormous practical value, because it enables seismologists to issue warnings to remote endangered coasts immediately after a seaquake and several hours before it arrives there. For example, an earthquake that occurred in Alaska generated a tsunami which, after traveling more than 3,800 miles (6,114 km), destroyed various coastal towns in Hawaii {Aleutian Islands 1946; \Rightarrow Fig. 4.1-R}.

Tsunamis that are generated in deep water radiate out at high speed from the triggering event. For example, at a water depth of 5,000 m, they propagate with a speed of about 800 km/h (220 m/s) – the speed of a jet airplane! Since the rate at which a wave loses its energy is inversely related to its wavelength, a tsunami will lose little energy as it propagates and can travel great distances. However, when it reaches the shallow water of a continental shelf, the wavelength of the tsunami shortens and its velocity drops tremendously due to friction with the sea bottom. For example, at a depth of 10 m, its velocity reduces to only about 36 km/h (10 m/s), which causes its front to compress into a towering wall of water. Shortly after crashing ashore and impacting buildings, an event which is often accompanied by a loud bang, the enormous masses of water flow back out to sea, thereby creating dangerous reverse currents. The impact forces from some tsunamis are enormous. Large rocks weighing several tons, along with boats and other debris, can be moved inland hundreds of feet by tsunami wave activity {MARCELLINUS \Rightarrow 365}. Tsunamis can also travel quickly up rivers and streams.

Coastal areas located close to the epicenter of a seaquake cannot be warned effectively because of the short arrival time of the resulting tsunami {Okushiri Earthquake \Rightarrow 1993}.

¹⁶³ E.D. SLOAN ET AL.: *Future of gas hydrate research* [Abstract]. EOS, Trans. Am. Geophys. Union **80**, No. 22, 247 (1999).

¹⁶⁴ According to this simple relationship, tsunamis in very deep water ($H > 11,400$ m) would propagate with supersonic speeds in relation to the velocity of sound in air at normal conditions. The Mariana trench, however, which is the deepest part of all of the Earth's oceans, only has a depth of about 10,910 m.

However, the much longer arrival times of tsunamis at remote coasts, up to several hours, allow the use of efficient early warning systems {Unimak Island \Rightarrow 1946}. Local and historical knowledge of earth- and seaquakes around the world has made it possible to create an International Tsunami Information Center (ITIC). Initiated in 1965 by the United States, this Center has proven to be of great benefit to all countries with Pacific coasts {ITIC \Rightarrow 1965}. A similar system does not yet exist for nations bordering the Atlantic and Indian Oceans, although the famous Lisbon Earthquake { \Rightarrow 1755}, and very recently the Sumatra-Andaman Islands Earthquake { \Rightarrow 2004}, demonstrated the enormous potential for destruction posed by tsunamis produced in coastal regions bordering these oceans in dramatic fashion.

A tsunami consists of a series of waves. Often the first wave may not be the largest. The danger from a tsunami can last for several hours after the arrival of the first wave. Usually the wave of greatest height is not the first one, but it most commonly occurs among the first ten waves or so. For example, during the Sumatra-Andaman Islands Earthquake { \Rightarrow 2004} the third wave of the tsunami was the most powerful and reached highest, occurring about an hour and a half after the first wave.

Tsunamis are not typically characterized by a steep, single front like a hydraulic jump: the arrival of a tsunami is sometimes indicated by a withdrawal of water which may be preceded by short-period, low-amplitude oscillations, known as “forerunners.”¹⁶⁵ In many cases it has been observed that a tsunami causes the water near the shore to first recede, similar to an extremely low tide, thus exposing the ocean floor {MARCELLINUS \Rightarrow 365}. Shortly after the Lisbon Earthquake { \Rightarrow 1755}, this strange phenomenon attracted curious people to the bay floor, where many of them were drowned by the subsequent wave crest that arrived only minutes later. A pronounced withdrawal of water from the shore has also been observed during the recent South East Asia tsunami disaster {Sumatra-Andaman Islands Earthquake \Rightarrow 2004}.

Tsunami animation is increasingly used to illustrate the generation and propagation of tsunamis produced by landslides, projectile impacts, asteroid impacts, and large chemical and nuclear explosions. In recent years, a collection of Tsunami Computer Movies was generated at Los Alamos National Laboratory using various numerical codes.¹⁶⁶ Some animations of tsunami propagation prepared by USGS and

Japanese researchers can be watched on the Internet; for example, a hypothetical tsunami generated in the U.S. Pacific Northwest,¹⁶⁷ and the tsunamis generated by the 1960 Chilean Earthquake¹⁶⁸ and the 2004 Sumatra-Andaman Islands Earthquake.¹⁶⁹

The effects of the force from a tsunami wave on structures have been modeled both numerically and in the laboratory. A review of previous work on this important subject was given by Nicolas HARITOS and colleagues at the 2005 Conference of the Australian Earthquake Engineering Society (AEES) held at Albury, New South Wales.

Surges. Sudden or violent changes of pressure in a gas, a liquid or a plasma are termed *surges*. They have been observed on Earth and also on the Sun. In the atmosphere, they are caused by sudden increases in the wind speed of a large wind stream, especially in the tropics (e.g., the so-called “surge of the trades” in the trade-wind belts or the “surge of the monsoon” in the monsoon currents).¹⁷⁰ A *storm surge* is simply water that is pushed towards the shore by the force of the high-speed winds swirling around the storm, resulting in exceptionally high water levels. It is generated by an extreme meteorological event, such as a winter storm or cyclone. When combined with *storm tides*; i.e., high-water levels above normal (astronomical) tide levels, such events create *hurricane storm tides* which can increase the mean water level by 15 feet (4.6 m) or more, causing severe flooding in coastal areas {FUJITA \Rightarrow 1981}. Storm surge flooding, a threat to many of the world’s coastlines, and one that presents a great potential for loss of life, can occur due to cyclones in the Bay of Bengal {G.H. DARWIN \Rightarrow 1898}, typhoons on the east coast of Japan, and hurricanes in the Gulf of Mexico and on the Atlantic coast of the United States.

In astronomy, surges are sudden, violent events that send jets of cool plasma into the Sun’s corona at speeds of up to 200 km/s along a straight or slightly curved path, thereby reaching heights up to 100,000 km.¹⁷¹

¹⁶⁵ T.S. MURTY: *Seismic sea waves. Tsunamis*. Bulletin 198, Dept. of Fisheries and the Environment. Fisheries & Marine Service, Ottawa, Canada (1977), p. x and 2.

¹⁶⁶ *Tsunami computer movies*. LANL, Los Alamos, NM (Oct. 2002); <http://t14web.lanl.gov/Staff/clm/tsunami.mve/tsunami.htm>.

¹⁶⁷ *An animation of a hypothetical tsunami generated by oblique slip*. USGS; <http://walrus.wr.usgs.gov/tsunami/QTanimation.html>.

¹⁶⁸ N. SHUTO: *Propagation of the earthquake-generated 1960 Chilean Tsunami across the Pacific*. Disaster Control Research Center, Tohoku University, Sendai, Japan; http://www.geophys.washington.edu/tsunami/general/historic/models_60.html.

¹⁶⁹ K. SATAKE: *2004 Indian Ocean Earthquake*. National Institute of Advanced Industrial Science & Technology (NIAIST), Tsukuba, Japan; <http://www.stormcenter.com/media/envirocast/tsunami/animation.gif>.

¹⁷⁰ *Encyclopædia Britannica, Micropædia*. Benton & Hemingway, Chicago etc. (1974), vol. IX, p. 690.

¹⁷¹ K. SHIBATA: *Surges*. In: (P. MURDIN, ed.) *Encyclopedia of astronomy and astrophysics*. Institute of Physics Publ., London etc., vol. 4 (2001), pp. 3258-3261.

Earthquakes and Seaquakes. *Earthquakes* are rather common natural phenomena in many countries and can occur at any time. Seaquakes occur in all oceans and also in some inland seas like the Mediterranean Sea. The term *seaquake* [*Seebeben*] was coined in the 1880s by Emil RUDOLPH {⇒1887}, a German geology professor at the University of Strassburg.

Surprisingly, the main causes of earth- and seaquakes were not discovered until the *plate tectonics revolution* of the 1960s. Based upon the theory of continental drift (Alfred WEGENER 1915), the theory of mantle thermal convection (Arthur HOLMES 1929), and the theory of “sea-floor spreading” (Harry HESS & Robert DEITZ 1961), it was recognized that the nature of the Earth’s surface is largely determined by the motions of rigid plates that slowly drift over geological timescales, and that the relative tectonic motions between adjacent plates give rise to large earthquakes along the plate boundaries. Large, devastating earthquakes – so-called “megathrust earthquakes” – are mostly of tectonic origin; they occur when one plate slips beneath another, a process termed *subduction*, which can generate significant tsunamis {Sumatra-Andaman Islands Earthquake ⇒2004}.

For example, the San Andreas Fault, a major fracture of the Earth’s crust close to the west coast of North America, and well known for producing occasional large earthquakes {San Francisco Earthquake ⇒1906}, is a result of shear between the Pacific and North American Plates.

Until the middle of the 18th century, naturalists drew their ideas on the mechanisms of earthquakes from contemporary records of the writings of some ancient philosophers {ARISTOTLE ⇒333 B.C.; SENECA ⇒A.D. 63; PLINY the Younger ⇒A.D. 79}. However, in England, in the “Year of Earthquakes” {⇒1750}, a remarkable series of earthquakes occurred which stimulated the imagination of British naturalists to explain their origin, and before the end of the year nearly 50 articles were communicated to the Royal Society in London. Only five years later, Lisbon {⇒1755} was destroyed by one of the largest earthquakes in recorded history. This disaster, which prompted investigations into its causes and proposals for possible countermeasures, happened towards the end of the Baroque period (ca. 1600–1780) – an era of strong contrasts, with much splendor and enjoyment on the one hand, and much escapism and *Memento mori* on the other. Many renowned naturalists, philosophers and even some poets commented on the disaster and started intellectual debates in attempts to find plausible reasons for it {DESMAREST, JACOBI, KANT, KRÜGER, LEBRUN, MAYER, ROUSSEAU, VOLTAIRE, all ⇒1756}. The Marquis de POMBAL, then Prime Minister of Portugal, survived the earthquake and

ordered an inquiry into the Lisbon Earthquake {⇒1755} and its effects to be established in all parishes of the country {⇒Fig. 4.1–E}; this inquiry may represent the birth of seismology, the scientific study of earthquakes.

The British geologist and astronomer John MICHELL {⇒1760}, today considered to be one of the founders of seismology, and the Dutch theoretician Antonius G. DRYFHOUT {⇒1766} tried to explain the Lisbon Earthquake by invoking some sudden explosions in the internal parts of the Earth. However, instead of assuming underground explosions of oxyhydrogen and quoting the sensational oxyhydrogen explosion experiment previously demonstrated publicly by the French alchemist Nicolas LÉMERY {⇒1700}, MICHELL postulated that earthquakes arose from subterranean fires which produced violent steam explosions upon contact with large quantities of water. He also explained the origins of seaquakes likewise, assuming that the sudden collapse of the roof over an subterranean fire produced the quake. He regarded volcanoes as useful “safety valves” which tended to prevent earthquakes by providing passage to high-pressure vapors.

Shortly after the Great Lisbon Earthquake, the German philosopher Immanuel KANT {⇒1756} attempted to deduce its cause. Although he initially erroneously followed LÉMERY’s volcanic hypothesis – then widely supported by other contemporary naturalists – he correctly recognized that the resulting great seismic sea waves (tsunamis) along the English, African, Caribbean and south European coasts were caused by a seaquake rather than by an earthquake. Very recently, KANT’s concept was partially confirmed by Charles L. MADER, a retired U.S. shock physicist from Los Alamos National Laboratory {Lisbon Earthquake ⇒1755}. Using tsunami wave characteristics to numerically simulate the possible source of the historical Lisbon Earthquake, MADER found that its epicenter may have been close to the 1969 earthquake epicenter located south of the Gorringe Bank, a region southwest of Portugal at the eastern end of the Azores-Gibraltar plate boundary.

Beginning in the early 1800s, the theory of elastic wave propagation was developed by CAUCHY, POISSON, STOKES, Lord RAYLEIGH and others who first described the main wave types to be expected in solid materials. These include compressional waves and shear waves, which are termed, respectively, *body waves* (because they travel through solid volumes) and *surface waves* (because they travel along free surfaces). Since compressional waves travel faster than shear waves and therefore arrive early on in a seismic event, they are termed *primary waves* (or *P-waves*), whereas the shear waves that arrive after are termed *secondary waves* (or

S-waves). The shearing ground motion caused by the *S-wave* produces no change in volume.

This complicated mixture of wave types, which is particularly pronounced in extended volumes like the Earth's crust, becomes much more apparent after they have propagated for sufficiently large distances. Seismic studies performed at large distances require either strong seismic shock sources (such as high explosives) or very sensitive seismic detectors. However, neither of these were available before the 1860s. On the other hand, laboratory studies, involving much smaller dimensions, were ruled out, because wave transit times would be only very short (on the order of hundreds of nanoseconds to tens of microseconds), which were not measurable until some 80 years later.

The scientific investigation of earthquakes did not begin until the middle of the 19th century, with the detailed study of the propagation, reflection and refraction of seismic shocks made by the Irish engineer Robert MALLETT {⇒1846} who also termed this new branch of geophysics *seismology*. Progress in this new discipline was significantly determined by *seismometry*, a new diagnostic technique concerned with the detection and measurement of seismic ground motions. It comprises the design of *seismographs*, their calibration and installation, and the quantitative interpretation of seismograms in terms of ground motion. The early history of seismometry up to 1900 has been reviewed in an excellent article written by James DEWEY¹⁷² and Perry BYERLY, two seismologists at the USGS National Earthquake Information Center in Denver, Colorado.

The seismic shocks generated by earthquakes produce not only violent vibrations and shakings of the ground but also audible sounds: near the source the sound sometimes includes sharp snaps; further away the sounds have been described as low and booming, like a distant clap of thunder or the boom of a distant cannon or explosion.

In seismology, the size of an earthquake is given by its magnitude M , a logarithmic measure. There are a number of different magnitude scales, such as those based on earthquake duration (M_d), locality (M_l), surface waves (M_s), body waves (M_b), and moment (M_w).¹⁷³ The moment magnitude M_w , which is calculated using the seismic moment, is now the one most commonly used to measure large-earthquake magnitudes {HANK & KANAMORI ⇒1979}.

Historically, seismologists assumed that a fault wouldn't break faster than the shear (or *S*) wave that radiates from an

earthquake's epicenter. Limits on the speed at which a rupture can propagate down a fault stem from past observations as well as assumptions about classical fracture mechanics and the material strength of rocks. Recent analyses of an historic earthquake {San Francisco Earthquake ⇒1906} and observations of earthquakes in California, Alaska, Turkey, and China {Kunlun Shan Earthquake ⇒2001} have given an inkling that a fault could break faster than the velocity of the shear wave, with rock motions outrunning the shear wave along a fault – a curious phenomenon called “supershear.” Researchers at CalTech demonstrated in laboratory experiments that *supershear fault rupture* is a real possibility rather than a mere theoretical construct {ROSAKIS ET AL. ⇒1999}. Using high-speed photography they recorded the rupture and stress waves as they propagated through their model fault, a set consisting of two plates of polymer material forced under pressure and a tiny wire inserted into the interface. In order to trigger the “earthquake” the wire was suddenly turned into an expanding plasma (exploding wire) by discharging a capacitor. The supersonic rupture produced a Mach cone similar to a projectile flying at supersonic speed {E. MACH & SALCHER ⇒1886}. In aerodynamics the Mach cone is characterized by a shock wave, a sudden increase in pressure. Similarly, in large earthquakes supershear may produce a sudden “super shake,” thus amplifying the destructive power of ground motion.

The discovery of supershear has complicated a relatively simple picture of how earthquakes unfold. Obviously, it requires more advanced theoretical models to better understand the conditions for supershear in terms of fault properties and earthquake magnitude, and to predict the length of travel before the transition to supershear.

Explosive Volcanic Eruptions. These are the most spectacular and most dangerous types of volcanic eruptions. *Explosive volcanic eruptions* are classified into four eruption types and, placed in order of increasing violence, they are termed:

- ▶ Hawaiian-type eruptions {Mt. Kilauea ⇒1959};
- ▶ Strombolian-type eruptions {Stromboli ⇒1930};
- ▶ Vulcanian-type eruptions {Vulcano ⇒1888}; and
- ▶ Peléan-type eruptions {Mt. Pelée ⇒1902}.¹⁷⁴

The lavas of volcanoes that erupt explosively are distinguished by their large viscosity and small mass diffusivity, which retard the release of dissolved vapors during eruption until the magma arrives at or near the Earth's surface, where

¹⁷² J. DEWEY and P. BYERLY: *The early history of seismometry (to 1900)*. Bull. Seismol. Soc. Am. **59**, No. 1, 183-227 (1969).

¹⁷³ *Recent earthquakes, glossary*. USGS, Earthquake Hazards Program; <http://earthquake.usgs.gov/recenteqsww/glossary.htm#magnitude>.

¹⁷⁴ H. SIGURDSSON (ed.): *Encyclopedia of volcanoes*. Academic Press, San Diego, CA (2000), pp. 249-269.

degassing can then be explosive. A volcano may also violently explode when

- ▶ the internal pressure of the gas and lava increases such that lava breaks through the flanks of the volcano. When the whole vent and the upper part of the magma chamber are rapidly emptied, the central, unsupported part may collapse, thus forming a “caldera;”
- ▶ ground water placed in contact with the magma is superheated, resulting in a violent steam-blast eruption; and/or
- ▶ the vent, which is initially blocked by a plug of solidified lava, is suddenly reopened by an increase in internal pressure, the dreadful “uncorking effect.” This prompts volcanic ejecta to exit at supersonic speeds.

Depending on the viscosity of the magma, the pressure and the gas content, extreme violent explosive eruptions may also induce atmospheric blast waves – known as “volcanic blasts” {Santorini \Rightarrow 1645 B.C.; Mt. Vesuvius \Rightarrow A.D. 79; Krakatau \Rightarrow 1883; Mt. Bandai-san \Rightarrow 1888; Mt. Pelée \Rightarrow 1902; Mt. St. Helens \Rightarrow 1980; Mt. Pinatubo \Rightarrow 1991}.

Furthermore, mass outflow occurring at supersonic speeds can provoke an energetic fragmentation of liquid magma into fine ash particles and their ejection into the upper atmosphere. Atmospheric shock waves (blasts) can damage structures far from their source: for example, directly by breaking windows, or indirectly by inducing ground shocks, which can damage buildings.¹⁷⁵

A *lateral blast* is produced by an explosive volcanic eruption in which the resultant cloud of hot ash and other material moves horizontally rather than upward. Lateral blasts can generate erosional phenomena in the surroundings of the crater – known as “furrows” {KIEFFER & STURTEVANT \Rightarrow 1988; STURTEVANT ET AL. \Rightarrow 1991} – which appear similar to high-speed ablation effects due to aerodynamic heating {JOULE & THOMSON \Rightarrow 1856; \Rightarrow Fig. 4.14–W} such as those observed at the nose of a body flying at supersonic speed. In Japan, a country which has more than 80 active volcanoes, many of them located very close to residential areas – shock wave dynamics is applied extensively to understand volcanic eruptions. Current studies encompass analog experiments into magma fragmentation, magma water vapor explosions, numerical simulations of explosive eruptions, and in situ blast-wave measurements. Very recently, Tsutomu SAITO¹⁷⁶ and Kazuyosjhi TAKAYAMA, two Japanese gas dynamicists,

reported on the application of a new 3-D computer code to an imaginary eruption of Mount Fuji (a 3,776-m-high strato-volcano about 100 km west of Tokyo), which provided useful information on how interactions of blast waves depend on the geometry of the ground.

It should be noted here that the term *blast* as used by geologists in the designations “volcanic blast” and “lateral blast” is not used in the strict sense defined by gas dynamicists for a point explosion resulting in a well-defined, steep-fronted, wave profile, but rather as a strong compressive atmospheric wave with amplitudes in the lower weak shock wave region. Just like in the case of thunder, the source of the blast is rather extended, and nonlinear propagation and refraction behavior of the ejecta-loaded and heated atmosphere as well as reflection effects at ground level mitigate the steepness of the emitted pressure waves. The nature of eruption-induced blasts was studied in more detail during the violent explosion of Mount St. Helens on May 18, 1980. Witnesses nearby did not observe any atmospheric shocks or sonic booms, which indicates that the furious blast, also called a “superheated hurricane” by some reporters, was subsonic. However, USGS geologists cautiously noted that “in some areas near the blast front the velocity may have approached, or even exceeded, the supersonic rate for a few moments” {Mt. St. Helens \Rightarrow 1980}. The late Bradford STURTEVANT (\Rightarrow 1991), a U.S. fluid dynamicist at CalTech, was a proponent of the idea that volcanoes could erupt supersonically.

One curious ejection phenomenon associated with explosive volcanic eruptions is known as a “volcanic bomb:” here, large individual fragments of molten lava ejected from the vent at high (supersonic) velocities in a viscous state are shaped during flight and assume an aerodynamically rounded form as they solidify before striking the earth. Various types of volcanic bomb can form, depending on the kind of volcanic material ejected, its temperature and viscosity, its gas content and its ejection velocity, *e.g.*, spheroidal bombs, ribbon bombs, spindle bombs (with twisted ends), and breadcrust bombs (with a compact outer crust or a cracked surface). Irregular flattish bombs that do not get hard before hitting the ground are called “pancake bombs” or “cow-dung bombs.”

Similar to the *Richter scale* {RICHTER \Rightarrow 1935} used to classify the magnitude (energy) of an earthquake, the *Volcanic Explosivity Index (VEI)* was introduced into volcanology in order to standardize the assignment of the size of an explosive eruption {NEWHALL \Rightarrow 1982}.

¹⁷⁵ R.P. HOBLITT, C.D. MILLER, and W.E. SCOTT: *Volcanic hazards with regard to siting nuclear-power plants in the Pacific Northwest*. USGS, Open-File Rept. No. 87-287 (1987).

¹⁷⁶ T. SAITO and K. TAKAYAMA: *Applying shock-wave research to volcanology*. Computing Sci. Engng. 7, No. 1, 30-35 (2005).

Meteorite Impact. Depending on the size and mechanical strength of the celestial body involved (comet, asteroid or meteoroid¹⁷⁷), a terrestrial impact can dramatically affect not only the close environment of the impact, but also remote areas as well. According to a widely accepted theory, the biggest terrestrial impact happened when the proto-Earth and a Mars-sized protoplanet collided with each other, eventually resulting in the creation of the Moon { \Rightarrow c.4.5 Ga ago}.

Meteorite impacts are sudden and violent natural phenomena. Many of these huge catastrophic impact events have occurred since the Earth was formed. Perhaps the most spectacular was one that happened long before the evolution of man; this impact created the *Chicxulub Crater*, some 170 km in diameter, and shaped the Yucatan peninsula. This event possibly led to the “Cretaceous-Tertiary mass extinction” {Chicxulub \Rightarrow c.65 Ma; ALVAREZ \Rightarrow 1978}, marking the end of the dinosaur era. In Germany, about 15 million years ago, a large meteorite, smaller than the one which created the Chicxulub Crater but certainly still large enough to cause massive effects, shaped the *Ries Basin* { \Rightarrow c.15 Ma ago; \Rightarrow Fig. 4.1–C}, a crater about 20 km in diameter that is located in northern Bavaria. This impact event was probably accompanied by a second, simultaneous impact nearby, which created the smaller *Steinheim Basin*, a unique crater structure with a central hill in the inner plain (a structure typically found in small lunar craters) {Ries Basin \Rightarrow c.15 Ma ago; \Rightarrow Fig. 4.1–C}.

Other huge terrestrial impact craters have also been identified elsewhere, e.g., the *Manicouagan Crater* (70 km in diameter, about 200 Ma) in northern Canada, one of the oldest and certainly largest impact events in Earth’s history. However, the total number of huge impact events that occurred throughout the evolution of man (< 3.5 million years ago) is still unknown, because only a small number of impact sites created within this period have been identified, such as the 10.5-km-diameter *Bosumtwi Crater* in central Ghana, which was created about 1.07 million years ago when primitive man had already fabricated stone tools via percussion in East Africa, only some 3,500 km away from the impact site.¹⁷⁸

Impact events caused by celestial objects that resulted in big crater structures killed most life in the surrounding area, and also must have affected the evolutionary course of man in more remote areas too. By the year 2000, almost 160 impact sites had been identified on Earth,¹⁷⁹ and this number is still increasing.

The most recent impact event of a significant magnitude happened on June 30, 1908 in Russia {Stony Tunguska \Rightarrow 1908}. Since this impact site is located in Siberia, in an isolated, almost uninhabited area, the occurrence of the event did not come to the attention of the international scientific community immediately. However, at 5.30 P.M. on the day of the collision, a series of unusual pressure waves in the atmosphere were recorded by microbarographs at Kew Observatory in England, and European seismographs also recorded a strong ground wave. The exact impact site was not investigated until 1928: the Russian scientist Leonid KULIK, who was selected by the Soviet Academy of Sciences to investigate what happened, led an expedition to the Tunguska region. He discovered a zone approximately 50 km in diameter that exhibited the effects of the intense heat produced by the meteorite, which was surrounded by another area 30 km in diameter where trees had been flattened by the air wave; these trees all pointed away from the central zone of the impact – a feature also observed more recently during the explosive eruption of Mount St. Helena { \Rightarrow 1980; \Rightarrow Fig. 4.1–G}. KULIK found a total of at least ten craters, ranging from 30 to 175 ft (9–53 m) in diameter, but searches to find the body of the meteorite were fruitless. An unusual meteorite fall was also observed in 1947 in the Sikhote-Alin Mountains, about 430 km northeast of Vladivostok {Sikhote Alin Meteorite \Rightarrow 1947}. The meteorite, which broke up during its passage through the atmosphere, causing violent explosions, produced a number of craters with diameters ranging from about 0.5 to 26 meters.

Fortunately, however, most meteoroids were small, and when entering the atmosphere they burned up by aerodynamic heating or fragmented into small pieces. This spectacular phenomenon of disintegration is often accompanied by a barrage of air shocks. The fall of a single meteorite, or sometimes the fall of a meteor swarm (a “meteoric shower”), is a spectacular event, and one which has long fueled superstitions and mystified man until very recently. In the late 18th century, the German physicist Ernst F.F. CHLADNI { \Rightarrow 1794}, today considered to be the father of acoustics,

¹⁷⁷ A *meteoroid* is a mass that orbits the Sun (or another star) or any other object in interplanetary space that is too small to be called an “asteroid” or a “comet.” A *meteorite* is a meteoroid that strikes the Earth (or another large body) and reaches the surface without being completely vaporized. One speaks of a *meteor* or *shooting star* when the mass is small enough to be totally destroyed in the atmosphere. Until two or three centuries ago, the term *meteor* included other phenomena such as halos, auroras and rainbows [after *Encyclopedia Americana*. Americana Corp., New York, vol. 18 (1974), pp. 713–716].

¹⁷⁸ In East Africa – the cradle of mankind – no meteorite impacts before this have been discovered. The only significant impact event that happened during the existence of prehistoric man was the Bosumtwi event in Ghana.

¹⁷⁹ A catalog and an atlas of impact craters around the world was prepared by the Geophysical Data Centre (GDC), Geological Survey of Canada. See *Impact cratering on Earth*; http://gdcinfo.aggr.nrcan.gc.ca/crater/paper/index_e.html.

also studied meteorites. Calling them “fireballs” [Germ. *Feuerkugeln*], he was apparently the first to maintain that meteorites really fell from the sky – as many observers claimed, but scientists denied. Eventually, investigations of the L’Aigle Fall {BIOT \Rightarrow 1803} carried out by a French commission firmly established that the stones did actually fall from outer space. However, this result was not immediately accepted by learned men. For example, the U.S. President Thomas JEFFERSON refused to believe that a meteorite that fell in Weston, Connecticut (in 1807) was extraterrestrial in origin. Accounts of the famous Washington Meteor (1873) that produced “short, hard reports like heavy cannon” provoked disputes among contemporary scientists about the possible causes of the shock phenomena observed {ABBE \Rightarrow 1877}. The Austrian philosopher Ernst MACH, who, together with the Austrian physicist Peter SALCHER discovered the ballistic head wave {E. MACH & SALCHER \Rightarrow 1886}, correctly explained that this “sonic boom” phenomenon was caused by the supersonic motion of the meteorite in the atmosphere {E. MACH & DOSS \Rightarrow 1893}.

But how were these meteorites produced in space? Some early natural philosophers proposed the idea that meteorites were ejecta from lunar volcanoes. Modern hypotheses on the formation of meteorites assume that they come from small masses of gas and dust which condensed in space due to gravity, or that they are the debris from larger, disintegrated bodies. After GALILEI’s first telescopic observations of the face of the Moon { \Rightarrow Fig. 4.1–A}, published in 1610,¹⁸⁰ it was generally supposed that lunar craters¹⁸¹ were artifacts of intelligent beings (Johannes KEPLER 1634), or were the result of volcanic action as proposed by Robert HOOKE { \Rightarrow 1665}, William HERSCHEL¹⁸² (1787), Johann Hieronymus SCHRÖTER { \Rightarrow 1802}, and James Dwight DANA¹⁸³ (1846). The idea that craters could be formed by the impact of “comets” was first conceived in the 1840s by the Bavarian astronomer and physician Franz VON PAULA GRUITHUISEN¹⁸⁴ [Germ. “*kometarischer Weltkörper*”], although the credit is generally given to

the British astronomer Richard A. PROCTOR { \Rightarrow 1873} in the literature. In the early 1890s, the U.S. geologist Grove K. GILBERT { \Rightarrow 1893} was the first to provide support for this idea through sound arguments, stating that the lunar craters, which he called “impact craters,” were generated by meteoritic impacts in the geologic past { \Rightarrow Fig. 4.1–A}. His impact hypothesis became the basis for all subsequent thinking along these lines; however, until the 1930s most astronomers still believed that the Moon’s craters were giant extinct volcanoes.

The first systematic studies of meteoritic material collected from various craters around the world {SPENCER \Rightarrow 1933} supported the impact theory {BUCHER \Rightarrow 1933; BOON & ALBRITTON \Rightarrow 1938}, particularly the discovery of the following geological structures:

- ▶ *Shatter cones* [Germ. *Strahlenkegel*], curiously striated conical geologic structures { \Rightarrow Fig. 4.1–C}, are formed when an intense shock wave travels through rock. Since they point toward the center of the impact, they provide some of the best macroscopic evidence for an impact.
- ▶ *Impactites* are composed of fused meteoric material and slag, but mostly of material from the impact site – so-called “target rock.” An *impactite* is a vesicular, glassy to finely crystalline geological material formed by the impact of a meteorite, asteroid or comet. This material often suffers shock metamorphism, which happens when a high-pressure shock wave passes through the target rock, generating pressures of over 40 GPa (400 kbar) at the point of impact.
- ▶ The sensational discovery of *coesite* {COES \Rightarrow 1953} and *stishovite* {STISHOV & POPOVA \Rightarrow 1961}, two high-pressure shock-induced polymorphs of quartz, in Arizona’s Meteor Crater¹⁸⁵ (now officially called

¹⁸⁰ G. GALILEI: *Siderius nuncius* (“The Starry Messenger”). Venice, Italy (March 4, 1610).

¹⁸¹ The word *crater* was first mentioned by the Ionian poet HOMER (c.8th century B.C.); it derives from the Greek word *krater* designating a vessel used for diluting wine with water. It was first used in 1791 to classify lunar surface phenomena by the German astronomer Johann Hieronymus SCHRÖTER (1745–1816). See § 507–516 in his *Selenotopographische Fragmente*. 2 vols, Lilienthal & Helmst, Göttingen (1791–1802).

¹⁸² W. HERSCHEL: *An account of three volcanos in the Moon*. Phil. Trans. Roy. Soc. Lond. 77, 229–232 (1787).

¹⁸³ J.D. DANA: *On the volcanoes of the Moon*. Am. J. Science & Arts 11, 335–355 (1846).

¹⁸⁴ F. VON PAULA GRUITHUISEN: *Der Mond und seine Natur* [Besonderer Abdruck aus seinem astronomischen Jahrbuche für 1848]. München (1848), p. 35.

¹⁸⁵ The famous *Meteor Crater* in Arizona { \Rightarrow c.50,000 years ago; \Rightarrow Fig. 4.1–B} is the most recently produced large terrestrial crater and certainly the most studied one. It was first made famous in 1891 due to the discovery of many masses of meteoritic iron scattered around it and the further discovery of diamonds inside these iron masses. Harvey H. NININGER, a famous U.S. meteorite hunter, wrote in his book *Arizona’s Meteor Crater*: “Formerly it was supposed that the early inhabitants had actually witnessed the event which produced the crater, but archaeologists seem now to be in agreement that man has been in this part of the continent only during the last 20,000 or 25,000 years.” Since modern geologists assume that Meteor Crater has an age of about 50,000 years, it is not very likely that the impact event was witnessed by prehistoric Arizonian hunters. The numerous arrow points picked up in the 1950s by NININGER were estimated by the Museum of Northern Arizona to be only about 800–900 years old. Some archeological evidence indicates that aborigines definitely lived in this area at least as early as 11,000 years ago. On the other hand, Robert S. DIETZ, a U.S. geologist, noted in his article *Astroblemes* [Scient. Am. 205, 51–58 (Aug. 1961)] that “the Hopi Indians are said to retain the legend that one of their gods descended here from the sky in fiery grandeur.”

“Barringer Crater”), constituted further evidence for meteoritic impact scars {CHAO, SHOEMAKER & MADSEN \Rightarrow 1960}. Shortly after, a very similar discovery was also made in the Ries Basin in Bavaria { \Rightarrow c.15 Ma ago; SHOEMAKER & CHAO \Rightarrow 1961; \Rightarrow Fig. 4.1–C}.

The term *astrobleme* was originally a Greek word meaning “star wound,” but it was later revived by the U.S. geologist Robert S. DIETZ to refer to scars on the Earth caused by meteoritic impacts. Astrobleme identification is based on finding the presence of the shock-induced structures mentioned above. Among the first terrestrial impact structures to have been identified as (probable) astroblemes were the *Bosumtwi Crater* in Ghana and the *Vredefort Ring*, the world’s largest impact crater structure, located in the Republic of South Africa {Vredefort Basin \Rightarrow c.2 Ga}. The astrobleme concept of developing criteria that could be used to recognize impact structures significantly promoted our knowledge of the geological history of the Earth, Moon, and other planets. An important milestone in the understanding of shock-induced geologic effects was reached at the First Conference on Shock Metamorphism of Natural Materials { \Rightarrow 1966}. Laboratory studies of shock metamorphism have long provided the basis for recognizing the diagnostic features of ancient terrestrial impact craters. However, Paul DECARLI,¹⁸⁶ a shock physicist at SRI, recently pointed out that there are significant differences between the range of parameters accessible in small-scale laboratory impact experiments and the conditions of large-scale natural impact events – in regard to both the peak pressures involved and the duration of the shock pressure.

Today we know that there are a huge number of small bodies in the Solar System, termed *near-Earth objects* (NEOs), with orbits that regularly bring them close to Earth and which, therefore, may someday strike our planet. Astronomers estimate that there are approximately one million bodies larger than 50 meters in diameter, a size which is generally considered to be the threshold for the body to be able to penetrate through the Earth’s atmosphere without fracturing. Several teams of international astronomers are currently surveying the sky with electronic cameras to find such NEOs and to quantify the danger of future Earth impacts. For example, the Catalina Sky Survey (CSS), based at the Lunar and Planetary Laboratory of the University of Arizona, is a consortium of three operating surveys aiming at discovering

comets and asteroids and identifying potentially hazardous NEOs. The omnipresent danger of collisions with NEOs became starkly apparent in 2002 when a celestial body about 100 m in diameter passed the Earth at a distance of only 120,000 km {Asteroid 2002 MN \Rightarrow 2002}.

In 1994, it became possible to observe the effects of a cosmic impact from a safe distance for the first time when a series of icy and stony fragments of comets impacted on Jupiter, spawning spectacular fireballs and producing impact scars that were visible to even amateur astronomers {Comet SHOEMAKER-LEVY 9 \Rightarrow 1994}.

Cosmic Shock Wave Phenomena. In ancient times, people thought of the night sky as being permanent, and the few changes that were observable with the unaided eye were usually repetitive, such as the changing phases of the Moon and the slow drift of the constellations. The positions of the stars were also regarded as being fixed and eternal. Besides the motion of a few “wandering stars,” later determined to be the planets, not much appeared to happen in the cosmos. Therefore, the occasional burst from an exploding star or the visit of a comet was a terrifying and portentous event.

In the past 50 years, however, astrophysics research using optical microwave and X-ray diagnostics has shown that dynamic phenomena are much more common in the cosmos than previously anticipated. Compared to terrestrial shock and detonation phenomena, cosmic dynamic processes reach enormous dimensions and relativistic velocities. For example, the *solar wind*, a stream of ionized gas particles emitted from the corona of the Sun, is our closest dynamic flow phenomenon of cosmic dimensions. It was first predicted by Prof. Eugene N. PARKER { \Rightarrow 1958} at the University of Chicago, a distinguished expert in the theory of cosmic magnetic fields. Only four years later, his hypothesis on the solar wind was confirmed experimentally {NEUGEBAUER & SNYDER \Rightarrow 1962}.

The solar wind, which is accelerated in the magnetic field of the Earth, produces a *bow shock* around the Earth {AXFORD \Rightarrow 1962; KELLOG \Rightarrow 1962; \Rightarrow Fig. 4.1–X}, which is analogous to the bow wave of a boat or the head wave of an object moving supersonically in the atmosphere.¹⁸⁷ The bow wave is a jump in plasma density, temperature and magnetic field associated with the transition from supersonic to subsonic flow. The *foreshock* is the region upstream of the bow shock, where energetic protons reflected back toward the

¹⁸⁶ P.S. DECARLI ET AL.: *Laboratory impact experiments versus natural impact events*. In: (C. KOEBERL and K.G. MACLEOD, eds.) *Catastrophic events and mass extinctions: impacts and beyond*. Geological Society of America, Special Paper No. 356 (2002), pp. 595-605.

¹⁸⁷ D. BURGESS: *Magnetosphere of Earth: bow shock*. In: (P. MURDIN, ed.) *Encyclopedia of astronomy and astrophysics*. Institute of Physics, Bristol etc. and Nature Publ. Group, London etc., vol. 2 (2001), pp. 1564-1568.

Sun from the shock may help to heat, decelerate and deflect the solar wind.

A similar boundary layer separates the heliosphere from interstellar space: at about 80–100 AU,¹⁸⁸ a *termination shock* is formed as the solar wind slows down from supersonic to subsonic speeds. The solar wind finally stops at the heliopause, the “stagnation” surface between the solar wind and the ions of the interstellar medium, which occurs about 130–150 AU from the Sun, and which forms the boundary of the heliosphere, the immense magnetic bubble containing our Solar System {Voyager 1 & 2 \Rightarrow 2003; Voyager 1 \Rightarrow 2004}.¹⁸⁹

Bow shocks also form around other planets of the Solar System {Mariner 4 \Rightarrow 1965; Voyager 2 \Rightarrow 1989; Cassini \Rightarrow 2004} as well as around hot young stars, where vigorous stellar winds slam into the surrounding interstellar medium { \Rightarrow Fig. 4.1–Y}.

Colliding and fusing galaxy clusters should produce *cosmic shock waves*. The outlines of these giant shock waves have now been seen as radioemitting structures.¹⁹⁰ Cosmic shock waves around distant clusters of galaxies could be generating some of the mysterious cosmic rays that strike Earth.

Accretion shock waves are spherical shock waves that arise when material (usually gas) spirals inward to a gravitational source. Accretion shocks arise in core-collapse supernovae, star formation, and accreting white dwarfs and neutron stars. In 2003, U.S. astrophysicists showed that small perturbations to a spherical shock front can lead to rapid growth of turbulence behind the shock, driven by the injection of vorticity from the now nonspherical shock. In 2007, they proposed a new explanation for the generation of neutron star spin which, for the first time, matches astronomical observations. Their results are based on simulations run on the Leadership Computing Facility Cray X1E at ORNL as part of the SciDAC TeraScale Supernova Initiative { \Rightarrow 2001}.¹⁹¹

Cosmic Explosion Phenomena. Shocks of much larger dimensions are generated during stellar explosions of dying stars, termed *supernovae* {BAADE & ZWICKY \Rightarrow 1931}. The earliest accounts of observations of a supernova (SN 1006), called a “guest star” at the time, can be found in Chinese and

Swiss annals a thousand years old {Guest Star \Rightarrow 1006}. The name *nova* – a shorthand for *nova stella* (from the Latin, meaning “new star”) – was coined by the German astronomer and mathematician Johannes KEPLER { \Rightarrow 1604}. He actually discovered an unstable star that was more than 100 times brighter than the modern definition of a nova; this was later recognized as being a supernova (SN) and was cataloged as SN 1604. Prior to KEPLER, the Danish astronomer Tycho BRAHE had already observed a supernova; today this is classified as SN 1572 {BRAHE \Rightarrow 1572}.

The most recent supernova that could be seen with the naked eye, named SN 1987A {SHELTON \Rightarrow 1987}, was discovered on February 23, 1987, in the Large Magellanic Cloud. Because of its relative proximity to Earth (only 168,000 light-years), SN 1987A became easily the best-studied supernova of all time. Supernovae are among the most energetic explosions in the Universe and can temporarily rival the energy release of an entire galaxy. Most of the energy, however, is not emitted as electromagnetic radiation, but rather in the form of kinetic energy imparted to stellar gases, which are accelerated into space, reaching relativistic velocities of up to one tenth of the velocity of light and causing discontinuities in pressure in the interstellar medium.

Supernova remnants, the remains of exploded stars, are actually hot gases that have been hurtled into space by the force of a supernova explosion. Some of these remnants are thousands of years old and many hundreds of light-years wide. For example, the famous Crab Nebula M1 (or NGC 1952) is the remnant of the supernova SN 1054. Many supernova remnants (SNR) have been found and cataloged. Supernova remnants are the major source of energy, heavy elements and cosmic rays in our Galaxy. In 1995, the National Radio Astronomy Observatory (NRAO) in Socorro, NM published the first “movie” showing the development of the remnant of SN 1993J in the galaxy M81 (or NGC 3031) over a period of one year from September 1993 to September 1994, as it expands with near-circular symmetry {DÍAZ \Rightarrow 1993}.¹⁹² An analysis of these “radio” images by NRAO researchers revealed that the debris shell of SN 1993J showed no signs of slowing due to interactions with material surrounding it yet. The material from the star’s explosion is moving at nearly 16,000 km/s. At that speed, the material would travel the distance from the Earth to Saturn in one day.

¹⁸⁸ The astronomical unit (AU) is the mean distance of the Earth from the Sun (ca. 150 million km).

¹⁸⁹ P. FRISCH: *The galactic environment of the Sun*. Am. Sci. **88**, No. 1, 52–59 (2000).

¹⁹⁰ T.A. ENBLIN: *Radio traces of cosmic shock waves*. Science **314**, No. 5800, 772–773 (Nov. 2006).

¹⁹¹ J.M. BLONDIN and A. MEZZACAPPA: *Pulsar spins from an instability in the accretion shock of supernovae*. Nature **445**, 58–60 (Jan. 4, 2007).

¹⁹² *Astronomers make “movie” of radio images showing supernova explosion*. National Radio Astronomy Observatory (NRAO), Socorro, NM (Nov. 30, 1995); <http://www.nrao.edu/pr/1995/supernovamovie/>.

One possible cause of the supernova phenomenon is that the core undergoes gravitational collapse, which generates a *pulsar* {HEWISH & BELL \Rightarrow 1967}, a rapidly spinning *neutron star* {LANDAU \Rightarrow 1932; BAADE & ZWICKY \Rightarrow 1934}. Experimental evidence for this was first provided by huge Čerenkov detectors located in the United States and Japan, which both recorded neutrino bursts from SN 1987A {SHELTON \Rightarrow 1987}. The name *pulsar* is an abbreviation of “pulsating radio star.” The detectable radiation from pulsars occurs entirely in the radio wavelength region of the electromagnetic spectrum, ranging from about 40 MHz to 2 GHz, with periods of about 33 milliseconds to 3.7 seconds. However, the pulsar in the Crab Nebula is so far the only remnant found to simultaneously emit radio, optical and X-ray pulses.

Stellar explosions that are even more powerful than supernovae are termed *hypernovae* {Beppo-SAX & CGRO \Rightarrow 1997; ROSAT \Rightarrow 1999}, and these are possibly the most powerful type of cosmic explosion to occur in the Universe since the Big Bang. A hypernova is an exceptionally large star which has collapsed because nuclear fusion is no longer taking place within its core. Its total collapse produces two highly collimated relativistic jets and is believed to creating a black hole rather than a neutron star. The concept of a hypernova was introduced by Bohdan PACZYŃSKI { \Rightarrow 1997}, an astrophysics professor at Princeton University, NJ, in order to explain gamma-ray bursts (GRBs).¹⁹³ The *collapsar* {GRB 030329 \Rightarrow 2003} is an extremely attractive model that fits a wide range of observed gamma-ray bursts. The *collapsar model* predicts highly beamed energy deposition responsible for the GRB along the symmetry axis.

These mysterious γ -ray burst phenomena were first observed by space-based military detectors {Vela Satellites \Rightarrow 1960}, and were later examined in more detail by three satellite observatories:

- ▶ NASA/ESA’s Hubble Space Telescope (HST), launched in 1990 and able to detect ultraviolet, visible and near-infrared wavelengths;
- ▶ NASA’s Compton Gamma-Ray Observatory (CGRO), launched in 1991 and dedicated to observing the high-energy Universe; and
- ▶ the ASI/NIVR BeppoSAX, an X-ray astronomy satellite, allowing observations in the spectral range 0.1–300 keV (launched in 1996).

Hypotheses on the origin of the tremendous energies observed in *quasars* are associated with stellar explosions, the gravitational collapse of massive stars, supernova explosions, the conversion of gravitational energy into particle en-

ergy by magnetic fields, matter-antimatter annihilation, and the rotational energy of a very compact mass (as proposed for pulsars). The term *quasar*, a contraction of “quasi-stellar radio source,” was originally applied only to the star-like counterparts of certain strong radio sources whose optical spectra exhibit red shifts that are much larger than those of galaxies {M. SCHMIDT \Rightarrow 1963}. Subsequently, however, a class of quasi-stellar objects was discovered with large red shifts that exhibit little or no emission at radio wavelengths. The term *quasi-stellar object* (QSO) is now commonly applied to star-like objects with large red shifts regardless of their radio emissivity. Based on the hypothesis that the quasar red shifts are cosmological and somehow related to the Big Bang – *i.e.*, that they are a consequence of the expansion of the Universe and thus directly related to the distance of the object {HUBBLE \Rightarrow 1929} – quasars are considered to be the remotest objects located at the edge of the visible Universe that are moving with very high velocities, approaching up to 80% the velocity of light.

It is generally agreed that the enormous energy emitted by quasars is gravitational and not thermonuclear in origin, and perhaps generated

- ▶ by multiple supernova outbursts, each supernova collapsing and releasing a large amount of gravitational energy;
- ▶ by collisions between stars; or
- ▶ by the gravitational collapse of a single supermassive star.

The energy source of a quasar is widely believed to be a supermassive black hole of several billion solar masses that is accreting matter from its surroundings; the black hole is surrounded by hot gas clouds revolving at speeds of up to several 1,000 km/s.

Cosmogony. The questions of the origin, the age and the evolution of the Universe have occupied man since the earliest times, but was not approached scientifically until the Age of Enlightenment, in the works of such eminent scientists as Thomas WRIGHT (1711–1786), Pierre-Simon DE LAPLACE (1749–1827) and Immanuel KANT (1724–1804). However, the foundations for such studies lie much further back in time: early contributions were made by Tycho BRAHE (1564–1601), Galileo GALILEI (1564–1642), Johannes KEPLER (1571–1630), René DESCARTES (1596–1650), and Sir Isaac NEWTON (1643–1727).

Based on his General Theory of Relativity, the German-born theoretical physicist Albert EINSTEIN (1879–1955) laid the mathematical foundations for the structure of the Universe as a whole {A. EINSTEIN \Rightarrow 1917}. He constructed a

¹⁹³ R. IRION: *Gamma beams from a collapsing star*. Science **283**, 1993 (March 26, 1999).

static model that was finite but unbounded and had a spherical geometry. The Russian physicist and fluid dynamicist Alexander FRIEDMANN { \Rightarrow 1922} noticed that EINSTEIN's field equations allowed two kinds of nonstatic solutions that are consistent with EINSTEIN's Cosmological Principle: these two models describing the dynamics of the Universe assumed either a negative spatial curvature, resulting in the continuous expansion of the Universe, or a positive spatial curvature, resulting in cycles of expansion and contraction – a Big Bang followed by a Big Crunch {DAVIES \Rightarrow 1994}.

Independently of FRIEDMANN's pioneering work, the Belgian mathematician, physicist and priest Georges LEMAÎTRE { \Rightarrow 1927} also published a paper on the cosmology of an expanding Universe resulting from the catastrophic explosion of an extremely high-condensed state containing all the matter of the Universe. Although expanding models of the Universe had previously been considered by other researchers, LEMAÎTRE's model, which assumed that the expansion would accelerate, has become the leading theory of modern cosmology. The discovery that galaxies were, in general, receding from us {HUBBLE \Rightarrow 1929} provided the first clue that the Big Bang Theory might be correct, and today FRIEDMANN and LEMAÎTRE are both considered to be the main founders of the Big Bang Theory.

Albert EINSTEIN, who welcomed FRIEDMANN's and LEMAÎTRE's results, then revised his cosmological model in the early 1930s, and, in cooperation with the Dutch astronomer Willem DE SITTER, constructed the simplest form of an expanding world model – the so-called “Einstein-de Sitter Universe” – a simple solution of the field equations of general relativity for an expanding Universe with zero cosmological constant and zero pressure.¹⁹⁴ Their homogeneous and isotropic model assumes that the Universe (i) expands from an infinitely condensed state at time $t = 0$ at such a rate that the density varies as $1/t^2$, and (ii) contains large amounts of matter that do not emit light and, therefore, had not been detected. This matter – now called “dark matter” – has since been shown to exist by observing its gravitational effects.

A further milestone in cosmogony was the development of the “Hot Big Bang Model” by the Russian-born U.S. physics professor George GAMOW and his collaborators Ralph A. ALPHER and Robert C. HERMAN, two young physicists {GAMOW, ALPHER & HERMAN \Rightarrow 1948}. Stating that the Universe began in a gigantic explosion, they predicted that there should be a relic radiation field from the Big Bang,

which resulted from the primordial fireball that LEMAÎTRE called *L'atome primitif* (“The Primeval Atom”) or *L'œuf cosmique* (“The Cosmic Egg”). Based upon EINSTEIN's General Theory of Relativity and his Cosmological Principle, the Hot Big Bang Model is supported mainly by two important observations:

- ▶ it predicts that the light elements (such as H, He and Li) should have been created from protons and neutrons just a few minutes after the Big Bang. The observed abundance of light elements, especially that of helium, is hard to explain without invoking this theory.
- ▶ The predicted background radiation was indeed discovered; it took the form of a residual black-body radiation at about 3 K {PENZIAS & WILSON \Rightarrow 1965}.

In February 2003, NASA released a “baby” picture of the Universe {NASA-GSFC \Rightarrow 2003; \Rightarrow Fig. 4.1–W}, the earliest ever taken, which captured the afterglow of the Big Bang. NASA scientists claimed that, based on an analysis of the data obtained for the cosmic microwave background, the Universe has an age of 13.7 ± 0.2 billion years. Previous theories on the age of the Universe were based upon the reciprocal of the Hubble constant (which is close to 10 billion years), and the ages of stars in globular clusters (which are among the oldest in the Universe), resulting in an uncertainty in the order of several billion years.

The British astronomer Fred HOYLE, who, like his colleagues and countrymen Hermann BONDI and Thomas GOLD, was an eager advocate of a rival steady-state relativistic cosmological model, was the first to (dismissively) call the expansion model the “Big Bang” {Sir Fred HOYLE 1940s, *see* BONDI \Rightarrow 1948}. The discovery of the excess microwave radiation, however, suggests that the steady-state model is incorrect and that the Universe as a whole changes over time.

Some modern cosmogonists assume that space, time and matter originated together, and that in the very initial phase of the explosion energetic photons created particle-antiparticle pairs which collided with each other, resulting in annihilation and their conversion into photons.

In the very early Universe, the temperature was so great that all of the matter was fully ionized and dissociated. Roughly three minutes after the Big Bang itself, the temperature of the Universe had rapidly cooled down from its initial phenomenal 10^{32} Kelvin to approximately 10^9 Kelvin. At this temperature, the production of light elements (namely deuterium, helium, and lithium) was able to take place – a process known as “Big Bang nucleosynthesis.” Elements heavier than helium are thought to have originated

¹⁹⁴ A. EINSTEIN and W. DE SITTER: *On the relation between the expansion and the mean density of the Universe*. Proc. Natl. Acad. Sci. U.S.A. **18**, 213 (1932).

in the interiors of stars that formed much later in the history of the Universe {Sir HOYLE \Rightarrow 1946}. David TYTLER¹⁹⁵ (an astrophysics professor at the Center for Astrophysics and Space Sciences, UC San Diego) and his collaborators reviewed the historical development of and recent improvements in the theory of Big Bang nucleosynthesis.

Big Bang cosmologists have devised a chronology for the history of our Universe {WEINBERG \Rightarrow 1977}, covering the period from 1.7×10^{-43} seconds after creation – the *quantum of time* or *Planck time* (PLANCK 1899),¹⁹⁶ the earliest known time that can be described by modern physics – up to the present time, and illustrating the main events on a diagram.¹⁹⁷ During this enormous time span, the initial temperature of about 10^{32} K decreased to the current background radiation temperature of only 2.725 K {PENZIAs & WILSON \Rightarrow 1965}.

2.3.2 EARLY MAN-MADE SHOCK GENERATORS: TOOLS AND TOYS

*I feel that E. MACH and B. DOSS give a correct interpretation of the cracking sound of a falling meteorite which, moving with great speed, is generated by the head wave. As a new example I would like to present the whip which, when skillfully used, also cracks; therefore we may conclude that the outermost end of the whip lash moves with a velocity which exceeds that of sound; i.e., it moves faster than 335 m/s. An experimental test confirmed my speculation.*¹⁹⁸

Otto LUMMER
Schlesische Friedrich-Wilhelms-Universität
Breslau 1905

Until the advent of gunpowder, the only means available for man to produce very loud sounds were the clapping of hands, whip-cracking, and belt-snapping.

Clapping of Hands. In his Ramsden Memorial Lecture on *Shock Waves*, Sir James Michael LIGHTHILL,¹⁹⁹ who was Beyer professor of applied mathematics at Manchester University and one of the leading British fluid dynamicists,

mentioned that “*weak shock waves* are produced by the clap of a hand... how fascinating at all ages from three months onwards is the capacity of a gentle movement of the hands to produce a pressure wave whose duration when it passes your ears is the thousandth part of a second, although echoes in a hall like this make it appear longer.” A strong hand clap is perceived by the ear as a sharp tone with a surprisingly high peak level;²⁰⁰ indeed, an *explosio* in its antique sense. However, the rise time of the pressure pulse is much less steep than that typical of a shock wave.

Whip-Cracking. Whip-cracking has probably been used since antiquity as an aid for drovers, tamers and coachmen, and as a children’s toy. Since the Middle Ages, whip-cracking has traditionally been practiced in southern Germany at Shrovetide to generate noise in contrast to Lent, a period of silence and contemplation, and it has been used for centuries in Switzerland for communication purposes. However, it was only rarely investigated by early scientists because the mechanism of shock generation in whip-cracking and its analysis are rather complicated. The German physicist Otto LUMMER { \Rightarrow 1905} was the first to speculate that the shock might be caused by supersonic motion of the whip tip. The solution to this riddle requires ambitious diagnostics and so it was not resolved until the advent of more advanced high-speed photography {CARRIÈRE \Rightarrow 1927; BERNSTEIN, HALL & TRENT 1958}. More recent experiments carried out at the Ernst-Mach-Institut (EMI) in Freiburg, using large-field-of-view shadowgraphy combined with laser stroboscopy and high-speed videography, have clearly shown that a shock wave is emitted from the whip tip (which does indeed move with a supersonic velocity of about 700 m/s), but that the decisive mechanism for generating strong reports is the abrupt flapping of the tuft at the turning point {KREHL ET AL. \Rightarrow 1995; \Rightarrow Fig. 4.5–K}. Although the shock wave quickly reduces in strength because of its spherical expansion, it is still perceived at a distance of many meters away as a sharp report, very similar to the one from a starter’s pistol.

Recently, it has been proposed that the tails of some dinosaurs were also capable of whip-cracking {ALEXANDER \Rightarrow 1989}. The giant sauropod dinosaurs of the family *Diplodocidae* were known to have enormous and graceful tails

¹⁹⁵ D. TYTLER ET AL.: *Review of Big Bang nucleosynthesis and primordial abundances* [with 194 refs.]. Phys. Scripta **85**, 12–31 (2000).

¹⁹⁶ All matter, energy, space and time are presumed to have exploded outward from the original singularity at $t = 0$. Nothing is known of the very earliest period of the history of the Universe: 0 to 1.7×10^{-43} seconds.

¹⁹⁷ P. SHELLARD: *A brief history of the Universe*. Cambridge Cosmology Hot Big Bang, Relativity & Gravitation Group, Cambridge University, U.K.; http://www.damtp.cam.ac.uk/user/gr/public/bb_history.html.

¹⁹⁸ See LUMMER { \Rightarrow 1905}.

¹⁹⁹ M. LIGHTHILL: *Shock waves*. Mem. Manch. Lit. Phil. Soc. **101**, 1–6 (1959).

²⁰⁰ According to Dr. Joachim FELDMANN at the Institut für Technische Akustik, TU Berlin, who kindly performed some measurements for the author, the peak pressures of a hand clap and a cap gun, recorded at a distance of 0.4 m using a Brüel & Kjær 1/4-in. (6.35-mm)-diameter capacitor microphone, amount to about 125 dB (0.36 mbar) and 138 dB (1.59 mbar), respectively. At these small overpressures the shock wave is still quite weak, propagating at practically the velocity of sound.

that tapered to thin tips. Nathan MYRHVOLD, chief technology officer and senior vice president of Advanced Technology at Microsoft, showed that computer modeling indicated that diplodocid tails could have reached supersonic velocities, and argued that this was physically plausible {MYRHVOLD & CURIE \Rightarrow 1997}. He was supported in his studies by Philip CURIE, a Canadian palaeontologist at the Royal Tyrrell Museum of Palaeontology in Drumheller, Alberta, Canada. Support for their hypothesis comes from the shape and mass distribution of the tail, which seem optimized for supersonic cracking. In addition, they speculated that a popper just a centimeter or two in length, made of skin and tendon, would improve shock wave generation and protect other tissues from the stress of cracking. They rather spectacularly concluded that, “Finally, we must confess that it is pleasing to think that the first residents of Earth to exceed the sound barrier were not humans, but rather the diplodocid sauropods. Following their demise, a hiatus in supersonic motion of over a hundred million years ensued until this capability was rediscovered by our species.”

Snapping Belts and Snapping Towel. The “snapping of belts” { \Rightarrow Fig. 4.11–A} is, much like the whip, another very primitive method of generating waves of finite amplitude in air. Its origin is unknown, but it might have been discovered by chance by primitive man when he learned to tan skins and fabricate smooth leather belts. When performed in an appropriate manner (*i.e.*, the ends of the two spread belts are pulled rapidly apart), the air enclosed between the belts is pushed to the sides, thus producing a loud sound. This simple device, more a toy than a useful tool, produces an impressive cracking sound in a more comfortable way than whip cracking does, although it is not as loud, and to some extent it even permits the emitted pulse to be tailored by varying the widths of the belts and their flexibility. Recently, this belt-snap phenomenon was investigated in more detail using a high-speed digital camera and a schlieren optical system of large aperture.²⁰¹ Results show that compression of the air between the two rapidly-approaching leather bands first causes a spherical shock wave to form near one hand. The compression then runs along the belt length toward the other hand at supersonic speed, producing a stronger oblique shock wave that is believed responsible for the audible crack.

The flicking of a wet towel produces not only a painful sting when applied to the skin, but when it is cast forth and withdrawn sharply in the right way it also produces a cracking sound in the air akin to shooting a gun. This cracking noise, a shock wave, is the result of the towel tip reaching supersonic velocities {LEE ET AL. \Rightarrow 1993}.

Electric Sparks. Compared with the purely mechanical means mentioned above, the application of electric sparks to generate shock waves is a rather new approach. After the invention of the electrostatic generator {VON GUERICKE \Rightarrow 1663} and the Leiden jar {VON KLEIST & CUNEUS \Rightarrow 1745}, it became possible for the first time to store considerable amounts of electric charge and to discharge them in a very short time. The discharge is typically accompanied by a spectacular flash and a sharp report, an impressive demonstration that, particularly in the era when the application of electricity was being pioneered, was often shown in university lectures and private circles, thus also stimulating discussions on the nature of lightning and thunder {WALL \Rightarrow 1708}. The electric spark proved to be not only very useful for generating shock waves at any time and in any space with any desired geometry, but it was also an alternative method to chemical explosives for generating shock waves, thus allowing one to differentiate between electrical and chemical secondary effects of observed shock wave interaction phenomena – an important advantage that, for example, considerably facilitated the interpretation of Mach reflection {E. MACH & WOSYKA \Rightarrow 1875}.

Musical Instruments. Although the sounds of many musical instruments are, in terms of intensity, still within the realms of acoustics, there are unique exceptions, such as some percussion instruments (*e.g.*, drums, bells, gongs) and some wind instruments (*e.g.*, whistles, sirens, horns). The latter can produce sounds with very large amplitudes, particularly when they are operated with pressurized air. The oldest account of the effects of intense sound waves is given in the Bible for the example of the “trumpets of Jericho”²⁰² – in modern terminology fanfares rather than trumpets. Prof. Gary SETTLES and collaborators at Penn State University used their unique large-scale schlieren system to visualize the weak shock wave emitted from a modern trumpet { \Rightarrow Fig. 4.5–N}.

²⁰¹ G. SETTLES, M. HARGATHER, M. LAWSON, and R. BIGGER: *Belt-snap shock wave*. 26th Int. Symp. on Shock Waves, Göttingen, Germany (July 2007), see abstract.

²⁰² (Probably around 1550 B.C.), on the seventh day, God told JOSHUA, MOSES' successor, to have the priests march around the walls of Jericho seven times, blowing their trumpets. The priests gave one long blast on their trumpets. The strong, thick walls of Jericho crumbled to the ground! JOSHUA and his armed men rushed across the rubble and took the city of Jericho (see the Holy Bible, Joshua 6:1–20).

2.3.3 BALLISTIC STUDIES: BIRTH OF SUPERSONICS

*The last particular I shall here take notice of, is a most extraordinary, and astonishing encrease of the resistance, and which seems in a manner to take place all at once, and this when the velocity comes to be that, of between eleven and twelve hundred feet in one second of time. This encrease however only concerns the absolute quantity of the resistance, the law of it continuing in other respects nearly the same as before: and it is remarkable farther, that the case wherein this encrease of resistance becomes observable, is that, wherein the velocity of the shot, is at least equal to that velocity with which sounds are propagated: whence Mr. Robins has with great sagacity offered his reasons to believe, that in this case the air does not make its vibrations sufficiently fast, to return instantaneously into the place the bullet has left; but that the bullet then leaves a vacuum behind it; whereby it becomes exposed to the whole resistance, the body of air before it is capable of giving...*²⁰³

Martin FOLKES
London 1747

In the early 16th century, ballistics reached an important milestone due to the introduction and general use of spherical iron shot fired from iron or bronze cannons, instead of massive stone shot. This “ballistic revolution” also started the so-called “terminal ballistics cycle,” which initiated improvements in weapon design and, in turn, new designs for protecting from such improved weapons:²⁰⁴ an effective self-supporting process which continues even now. For example, with the advent of modern high-quality concrete – based on the invention of Portland-cement made by the English mason Joseph ASPDIN (1824) and on the idea of reinforcing concrete by metal wires (“ferroconcrete”), an invention of the French gardener Joseph MONIER (1867) – a low-cost and effective material for protecting against heavy impact became available. It was first used to strengthen military positions against artillery attacks on a large scale between the two World Wars to construct the French Maginot Line in the 1930s and the German West Wall in the period 1938–1939. On the other hand, the increasing use of concrete in the construction of fortifications and shelters stimulated military engineers to develop “superguns” in both World Wars {⇒ Fig. 4.2–T}. Recent developments in bunker- and tunnel-busting weapons include “thermobaric” bombs which use the combined effects

of heat and explosive pressure against certain types of tunnel targets to maximize the kill rate {NAGLE ⇒ 2002}.

The steady progress made in gun technology over more than six centuries has improved gunshot reliability and reproducibility, both of which are important preconditions for deriving empirical laws. Beginning in the 17th century, gunnery evolved into a science of its own and the gunner into a lauded expert in applied mechanics, then the most advanced discipline of physics. High-ranked artillerymen were often graduates from prestigious polytechnic schools or military academies, well trained in physics and higher mathematics. Early ballisticians had already noticed the importance of aerodynamic drag and its dependence on projectile geometry and velocity, which is essential for precise aiming. Sir Isaac NEWTON was the first to study the problem of fluid resistance on a scientific basis. He stated that the resistance depends on three factors: the density of the fluid, the velocity, and the shape of the body in motion. In his *Principia* {Sir NEWTON ⇒ 1687}, he specified that the resistance of a body moving through a fluid consists of three parts: a first part which is constant, a second part which is proportional to the velocity, and a third part which is proportional to the square of the same, the latter part being the most important.²⁰⁵

At low speeds, the air behaves like an incompressible fluid. The classical theory of hydrodynamics, which involves no viscosity and is concerned only with irrotational motion (i.e., motion where the vorticity is zero everywhere), predicts that a body moving steadily will experience no resistance or lift. At higher speeds, however, energy is increasingly dissipated, so that bodies moving at speeds faster than that of sound encounter considerable resistance. Up to the 18th century, the aerodynamic drag of bodies was measured by timing their free fall, mounting the body on a pendulum, or suspending the body in a flow. The English military engineer Benjamin ROBINS devised a rotating arm machine that permitted the rotation of the test object in a reproducible manner by means of a falling weight. ROBINS {⇒ 1746} also performed systematic aeroballistic studies at substantial velocities and first measured the supersonic velocity of a musket ball – thus giving birth to a new discipline of fluid dynamics: *supersonics*.

The British mathematician and gun expert Charles HUTTON {⇒ 1786} followed in ROBINS’ footsteps; he first extended the ballistic pendulum technique to cannon shots, and he measured supersonic velocities as well. In 1932, the famous Hungarian-born U.S. aerodynamicist and applied

²⁰³ From the *laudatio* given by Martin FOLKES, then President of the Royal Society of London, on the occasion of awarding the Copley Medal to Benjamin ROBINS. See J. WILSON: *Mathematical tracts of the late Benjamin ROBINS*. Nourse, London, vol. 1 (1761), *Preface*, p. xxix.

²⁰⁴ L.W. LONGDON: *Terminal ballistics*. In: (R. VINCENT, ed.) *Textbook of ballistics and gunnery*. H.M.S.O., London, vol. 1 (1987), pp. 641–644.

²⁰⁵ See his *Principia*, *Lib. II, Scholium* at the end of Sections I and III, respectively.

mathematician Theodore VON KÁRMÁN,²⁰⁶ who coined the term *wave drag* for a new type of drag encountered at supersonic velocities, appropriately called these pioneering studies of early ballisticians “the theoretical-empirical preschool of supersonic aerodynamics.”

In the following period, drag research proceeded along three main lines:

- ▶ measurement of the drag force as a function of the body’s geometry and velocity – a difficult and cumbersome enterprise, particularly in the early days of high-speed instrumentation;
- ▶ derivation of general (mostly empirical) rules from these data for practical applications; and
- ▶ the development of a general dynamic theory of drag.

In the literature, the history of drag research has been illuminated from both a historical^{207, 208, 209} and a ballistic²¹⁰ viewpoint. In his famous review article *Ballistik* (“Ballistics”) written for the Encyclopedia of Mathematical Sciences (1901), the German physicist and patriarch of ballistic research Carl CRANZ²¹¹ addressed both historic and ballistic aspects of previous drag research. In a single diagram he compared data for drag vs. velocity obtained from measurements on various projectile geometries {⇒Fig. 4.14–M}. He thus illustrated that drag initially increases strongly in the transonic regime, but after passing through the “sound barrier” {HILTON ⇒1935}, at which the projectile equals the velocity of sound in the surrounding air, it decreases. His diagram also nicely demonstrated the high standard of ballistic drag research at a time when high-speed drag research in aeronautics²¹² was still some way off, and even the feasibility of motor flight had not yet been proven {WRIGHT Bros. ⇒1903}. In addition, it clearly showed that the transonic phase ($M = 0.7$ – 1.3) is of great practical importance in both ballistics and high-speed aeronautics.

2.4 EVOLUTION OF SHOCK WAVE PHYSICS

*A shock wave is a surface of discontinuity propagating in a gas at which density and velocity experience abrupt changes. One can imagine two types of shock waves: (positive) compression shocks which propagate in the direction where the density of the gas is a minimum, and (negative) rarefaction waves which propagate in the direction of maximum density.*²¹³

Gyözy ZEMPLÉN

Műegyetem (Royal Josephs Polytechnic)
Budapest 1905

SHOCK WAVES are constant companions in most high-speed events and arise when matter is subjected to rapid compression – for example, by the violent expansion of the gaseous products from a high explosive or by an object moving faster than the speed of sound in the surrounding fluid. The large number of disciplines that now fall into the category of shock wave research did not evolve along a straight path to their present state. Rather, they emerged from complex interactions among shockwave-related disciplines, or independently from other branches of science {⇒Fig. 2.12}. One practical means of obtaining a useful survey of the development of shock wave physics is to classify the large number of milestone achievements and observed phenomena in terms of states of matter {⇒Fig. 2.11} – *i.e.*, shock waves in gases, liquids, solids, and plasmas. The following paragraphs will refer to the first three states of matter only.

2.4.1 NONLINEAR ACOUSTICS

Gas dynamics, a field of shock wave physics relating to the gaseous state, emerged from *nonlinear acoustics* – a particular branch of acoustics covering all such acoustical phenomena which are amplitude-dependent due to the nonlinear response of the medium in which the sound propagates; *i.e.*, phenomena which are beyond classical acoustics and can no longer be described by the infinitesimal theory.

It is quite possible that early acousticians reflected on some of the unusual phenomena associated with intense sound. Sound waves propagate linearly only when both their

²⁰⁶ Th. VON KÁRMÁN: *Höher, schneller und heißer*. Interavia **11**, 407 (1956).

²⁰⁷ O. FLACHSBART: *Geschichte der experimentellen Hydro- und Aeromechanik, insbesondere der Widerstandsforschung*. In: (L. SCHILLER, ed.) *Handbuch der Experimentalphysik*. Akad. Verlagsgesell., Leipzig, vol. IV, 2 (1932), pp. 1–61.

²⁰⁸ A.R. HALL: *Ballistics in the seventeenth century*. Cambridge University Press, Cambridge (1952).

²⁰⁹ R. GIACOMELLI and E. PISTOLESI: *Historical sketch*. In: (W.F. DURAND, ed.) *Aerodynamic theory*. Dover Publ., New York, vol. 1 (1963), pp. 305–394.

²¹⁰ C. CRANZ: *Äußere Ballistik*. Springer, Berlin, vol. 1 (1925), chap. 2.

²¹¹ C. CRANZ: *Ballistik*. In: (F. KLEIN and C. MÜLLER, eds.) *Enzyklopädie der mathematischen Wissenschaften*. Teubner, Leipzig (1901–1908), vol. IV: *Mechanik*. Part 18, pp. 185–279.

²¹² According to NASA-GSFC, the term *aeronautics* [French *aéronautique*, derived from the Greek words for “air” and “to sail”], being concerned with flight within the Earth’s atmosphere, originated in France.

²¹³ This modern and concise definition of a shock wave was first given by the young Hungarian physicist G. ZEMPLÉN {⇒1905}. Visiting Germany and France on a research fellowship (1904–1906), his interest in shock waves was obviously stimulated by the mathematicians Felix KLEIN, Pierre DUHEM and Jacques HADAMARD.

amplitudes are very small *and* the times and distances over which they are observed are not too great.²¹⁴ If either of these conditions is violated, one may have to account for nonlinear effects, which result in severe waveform distortion. The first condition of large disturbance amplitudes is quite familiar to shock physicists. The second condition requires comment. Curiously, in nonlinear acoustics the steepening of initially small disturbances is a cumulative, long-duration evolutionary process that might be very small after a single wavelength but may grow into a serious distortion after the wave has propagated a distance of thousands of wavelengths. In shock wave physics, however, the waveform is confined to a single pulse – for example, in the case of a blast wave of the Friedlander type {FRIEDLÄNDER \Rightarrow 1946}, and in sonic booms of the N-wave type {DUMOND \Rightarrow 1946} – and the steepening process, favored by the larger pressure amplitudes involved, is confined to shorter distances, unless the shock wave is heavily damped by dissipation and geometrical expansion.²¹⁵

The British professor Sir Richard SOUTHWELL,²¹⁶ while commemorating at the University of Glasgow the centennial of RANKINE's appointment to the Queen Victoria Chair of Civil Engineering and Mechanics, addressed the peculiarities of nonlinearities in acoustics, making the interesting comment that words spoken at a civilized volume will pass through a speaking tube unaltered, but they become increasingly distorted when the volume is raised. Prof. Robert T. BEYER²¹⁷ at Brown University, who discussed the early history of nonlinear acoustics and reviewed modern achievements, appropriately wrote, "Only a few decades ago, nonlinear acoustics was little more than the analysis of shock waves and large-amplitude mechanical vibrations. Gradually, however, more and more of acoustics has been examined for its nonlinear aspects until today one can write a nonlinear supplement to virtually every chapter of a text on acoustics and vibrations..."

Modern nonlinear acoustics is said to comprise the fields of

- ▶ aeroacoustics (the study of noise generation);
- ▶ finite-amplitude waves, understood by acousticians as being the branch of acoustics lying between linear acoustics and weak shock waves;
- ▶ shock waves;
- ▶ phenomena associated with the passage of intense sound beams, such as radiation pressure, streaming and cavitation; and
- ▶ nonlinear acoustic phenomena resulting from the presence of cracks in solids, which can be used in crack diagnostics.²¹⁸

Obviously, for shock physicists treating gas dynamics, the close relationship to nonlinear acoustics is striking, and modern literature on acoustic research – such as papers published in the journals *JASA* (since 1929) and *Acustica* (since 1951), and in the proceedings of the *International Congress on Acoustics* (since 1953) – continues to be a rich source of information.

2.4.2 MAIN PERIODS OF EVOLUTION

From a historical point of view, the evolution of modern shock wave physics can be roughly divided into seven partly overlapping periods:

From 1746 to 1808. The birth of supersonic aeroballistics, beginning with drag studies of musket shots {ROBINS \Rightarrow 1746} and later of gun shots {HUTTON \Rightarrow 1783}. Scientific discussions are initiated regarding whether sounds of finite amplitude propagate differently to sound waves of infinitesimal amplitude {EULER \Rightarrow 1759}. The method of characteristics is developed which, much later, will prove most useful in gas dynamics and high-speed aerodynamics for solving first-order partial differential equations, particularly of the hyperbolic type {MONGE \Rightarrow 1770s}.

From 1808 to 1869. Measurements of the velocity of sound in air are performed using a gun; it is observed that at a large distance from the gun the command "Fire" is heard *after* the report of the gun, which proves that loud sounds must propagate supersonically {PARRY \Rightarrow 1824/1825}. A first mathematical theory for *waves of finite amplitude*, later termed *shock waves*, is developed {POISSON \Rightarrow 1808; AIRY \Rightarrow 1848 & 1849; CHALLIS \Rightarrow 1848; EARNSHAW \Rightarrow 1858 & 1860; RIEMANN \Rightarrow 1859; RANKINE \Rightarrow 1869}.

²¹⁴ D.G. CRIGHTON: *Propagation of finite-amplitude waves in fluids*. In: (M.J. CROCKER, ed.) *Encyclopedia of acoustics*. Wiley, New York etc., vol. 1 (1997), pp. 203-218.

²¹⁵ In the acoustic case, the pressure p of a spherical and cylindrical wave decays with distance r from the source according to $p \sim 1/r$ and $p \sim 1/r^{0.5}$, respectively, while for a point and a cylindrical explosion the shock wave pressure decays according to $p \sim 1/r^3$ and $p \sim 1/r^2$, respectively {TAYLOR \Rightarrow 1941; LIN \Rightarrow 1954}.

²¹⁶ R. SOUTHWELL: *W.J.M. RANKINE: a commemorative lecture delivered on 12 December, 1955, in Glasgow*. Proc. Inst. Civ. Eng. (Lond.) **5**, 178-193 (1956).

²¹⁷ R.T. BEYER: *Nonlinear acoustics*. Acoustical Society of America, Woodbury, NY (1997).

²¹⁸ A.M. SUTIN and V.E. NAZAROV: *Nonlinear acoustic methods of crack diagnostics*. Radiophys. Quant. Electr. **38**, No. 3-4, 109-120 (1995).

From 1822 to 1893. This is the classical era of pioneering experimental studies, ranging from more precise measurements of the velocity of sound in the free atmosphere performed using the muzzle blasts from firearms {Bureau des Longitudes \Rightarrow 1822} to the first measurements of the velocities of shock waves. First experimental evidence is provided that a shock wave does indeed propagate supersonically {REGNAULT \Rightarrow 1863}, as later confirmed by laboratory-scale experiments using electric sparks and small amounts of high explosives {E. MACH & SOMMER \Rightarrow 1877}. Schlieren observations made using a stroboscopic method reveal that a spark discharge in air is surrounded by a wave with a sharp front, the so-called “shock wave” {A. TOEPLER \Rightarrow 1864}. This period also sees various discoveries of shock wave effects that had been unknown previously in linear acoustics, such as the dependency of velocity of the shock wave on the shock strength {E. MACH & SOMMER \Rightarrow 1877}, and the discovery of *irregular reflection* {E. MACH & WOSYKA \Rightarrow 1875}, later to be called the “Mach effect” {E. MACH & WOSYKA \Rightarrow 1875}. A dimensionless parameter is proposed in order to distinguish among laminar and turbulent flow regions, later called the “Reynolds number” {REYNOLDS \Rightarrow 1883}. The predicted head wave phenomenon {DOPPLER \Rightarrow 1847} is first experimentally proved using schlieren photography {E. MACH & SALCHER \Rightarrow 1886} and shadowgraphy {BOYS \Rightarrow 1890}. The Rankine-Hugoniot shock theory is established {RANKINE \Rightarrow 1869; HUGONIOT \Rightarrow 1887}. The first photographs of a shock wave, generated by the discharge of a Leiden jar in air, are obtained using gelatin dry plates {E. & L. MACH \Rightarrow 1889}. The Mach-Zehnder interferometer is invented {L. MACH & ZEHNDER \Rightarrow 1891} and five years later first used to measure the density distribution around a supersonic bullet {L. MACH \Rightarrow 1896}. It is recognized that the sharp report accompanying the fall of a meteorite is caused by the head wave phenomenon {E. MACH & DOSS \Rightarrow 1893}.

From 1888 to 1930. This is an era of refined, more systematic experimental and mathematical studies on the nature of shock waves, particularly on shock waves in air. The invention of the Laval nozzle {DE LAVAL \Rightarrow 1888} tremendously stimulates the construction of more efficient steam turbines and initiates supersonic flow studies inside and outside of nozzles of various geometry. First investigations of supersonic free air jets using high-speed photography reveal a “lyre” pattern of reflected shock waves, later called “shock diamonds” {SALCHER & WHITEHEAD \Rightarrow 1889}; these studies prompt the idea of using a supersonic blow-down wind tunnel {SALCHER \Rightarrow 1889}. It is recognized that a supersonic

flow passing around a sharp corner expands through a “fan” of Mach lines centered at the corner, later called the “Meyer-Prandtl expansion fan” {MEYER & PRANDTL \Rightarrow 1908}. It is first demonstrated theoretically that a shock wave may propagate as a condensation or as an expansion {DUHEM \Rightarrow 1909}. A dimensionless parameter is introduced that characterizes a fluid property in the regime of convection, later called the “Prandtl number” {PRANDTL \Rightarrow 1910}. In the late 1920s, investigations originating from the practical needs of aeroballistics (minimization of wave drag), aeronautics (high-speed propellers) and steam turbine development (optimal Laval nozzle geometry) eventually lead to the establishment of *gas dynamics*, a new branch of fluid dynamics. The first supersonic wind tunnel is set in operation {STANTON \Rightarrow 1921}. A dimensionless parameter characterizing the flow velocity with respect to the sound velocity of the surrounding (quiescent) medium is introduced; this is later called the “Mach number” {ACKERET \Rightarrow 1928}. A non-stationary cosmological model is also first proposed in this period {FRIEDMANN \Rightarrow 1922; LEMAÎTRE \Rightarrow 1927}, which later resulted in the famous *Big Bang* theory on the origin of the Universe.

From 1930 to 1939. This period is the early era of high-speed aviation and supersonic wind tunnel testing, which reaches its first culmination at the 5th International Volta Congress {Rome \Rightarrow 1935}, where numerous researchers from prestigious research institutes around the world present their pioneering contributions on this subject. In the following years, a number of unique transonic and supersonic wind tunnels will be set in operation {ACKERET \Rightarrow 1933; BUSEMANN & WALCHNER \Rightarrow 1933; WIESELSBERGER \Rightarrow 1934; HVA Peenemünde \Rightarrow 1939}.

From 1939 to 1949. This era is characterized by an enormous growth in shock wave research (when then also included the solid state) – research of the highest priority that is almost exclusively initiated to satisfy military needs. Large groups or teams of research workers are formed to concentrate effort on individual problems; such team research will become a common feature of postwar science. Though relatively brief and suffering from a shortage of trained personal, time and money, this era revives interest in the shock tube technique {BLEAKNEY \Rightarrow 1946}, air blast {G.I. TAYLOR \Rightarrow 1941; KENNEDY \Rightarrow 1946; SLADE JR. \Rightarrow 1946; Helgoland Blast \Rightarrow 1946; Texas City Explosion Disaster \Rightarrow 1947}, sonic booms {DUMOND \Rightarrow 1946}, underwater explosions {DTMB & Kriegsmarine \Rightarrow 1941; KIRKWOOD & BETHE \Rightarrow 1942; Operation CROSSROAD \Rightarrow 1946}, and shock wave interaction phe-

nomena such as the Mach effect {VON NEUMANN \Rightarrow 1943; SPITZER & PRICE \Rightarrow 1943; WOOD \Rightarrow 1943; CHARTERS \Rightarrow 1943; L.G. SMITH \Rightarrow 1945}. The first hypersonic flow studies performed close to Mach 9 are carried out in a modified supersonic wind tunnel {ERDMANN \Rightarrow 1943/1944}.

This era is also characterized by the design and testing of atomic bombs {Trinity Test \Rightarrow 1945; Semipalatinsk-21 \Rightarrow 1949} and their first military use to destroy whole cities {Hiroshima & Nagasaki Bombing \Rightarrow 1945}. In Germany, the United States and England, the new types of engines for use in aircraft, missiles and rockets are developed, such as the pulsejet {P. SCHMIDT \Rightarrow 1930}, transonic aircraft {WARSITZ (Heinkel 176) \Rightarrow 1939; Messerschmitt AG (Me 163 \Rightarrow 1941 & Me 262 \Rightarrow 1942); GILKE (Lockheed P-38) \Rightarrow 1941 & 1945}, anti-aircraft supersonic missiles {HVA Peenemünde \Rightarrow 1939} and large supersonic rockets {HVA Peenemünde \Rightarrow 1942}, two-stage rocket {1949, \Rightarrow Fig. 4.20–D}, and supersonic aircraft {YEAGER (Bell XS-1) \Rightarrow 1947}.

Shock wave physics proves to be an indispensable tool in nuclear weapons technology, thus initiating modern solid-state shock wave physics {GORANSON \Rightarrow 1944} and detonation physics {ZEL'DOVICH \Rightarrow 1940; DÖRING (Secret Workshop “Probleme der Detonation”) \Rightarrow 1941; KISTIAKOWSKY \Rightarrow 1941; VON NEUMANN \Rightarrow 1942; DÖRING \Rightarrow 1943; JOHNSTON \Rightarrow 1944; LANDAU & STANYUKOVICH \Rightarrow 1945}. This, in turn, also stimulates significant advances in submicrosecond high-speed diagnostics {REYNOLDS \Rightarrow 1943; “pin method” \Rightarrow 1944; LIBESSART \Rightarrow 1944}, and ultrahigh-speed photography {STEENBECK \Rightarrow 1938; Trinity Test (BRIXNER) \Rightarrow 1945; C.D. MILLER \Rightarrow 1946}. Last but not least, various electronic computing machines are developed in the U.S.A., U.K. and Germany in the 1940s in order (amongst other reasons) to solve the *hydrodynamic equations* (or *shock wave equations*) used in nuclear bomb physics (see Sect. 2.9.2).

From 1950 to the Present. The postwar era, the most complex one, is characterized by the establishment of a large number of governmentally and privately operated research institutes. Shock wave research becomes intimately connected with industry, defense, and politics, thus rendering the classical ideal of pure science obsolete. Almost all research dedicated to all branches of shock and detonation physics is now done by highly trained experts, employed wholly or mainly for this work within such special institutions. Due to competition, there is also a general tendency for research workers to become very specialized. On the other hand, independent individual research and invention – still one of the main pillars of progress in science and technology in the 19th century – has degraded to a curiosity.

The tremendous progress made in shock wave physics, which has already provided an enormous body of worthwhile fundamental theoretical and practical knowledge, further promotes interdisciplinary research in a unique manner. It stimulates new branches within the classical sciences such as in astronomy and astrophysics, cosmology and cosmogony, geology and geophysics, and even in medicine and biology.

This era sees many spectacular milestone achievements in practical aeronautics and astronautics built upon the foundations laid in previous eras. The spectacular first hypersonic manned space flight {GAGARIN \Rightarrow 1961} demonstrates that reentry at hypersonic speed can be successfully controlled. In the same year, the U.S. hypersonic research aircraft makes its first successful hypersonic flight {X-15 \Rightarrow 1961}. With the development of supersonic airliners {Tupolev Tu-144 \Rightarrow 1968; Concorde \Rightarrow 1969}, the experience of flying supersonically becomes routine: regular civil supersonic flights from British Airways and Air France begin in 1976 but end in 2003 because of the age of the aircraft, possibly terminating the spectacular era of supersonic civil transportation forever.

In the 1950s, cosmic gas dynamics develops into an important branch of astrophysics. Numerous space research programs as well as military interests stimulate studies in hypersonic aerodynamics, reentry and hypervelocity impact. In the 1960s – perhaps the Golden Age of funding – research in shock physics enters new dimensions, reaching its culmination with the first manned flight to the Moon {Apollo 11 \Rightarrow 1969}. The discovery of shock polymorphism in meteorite craters {CHAO, SHOEMAKER & MADSEN \Rightarrow 1960}, which advances our understanding of the Earth's past, also initiates numerous astrogeological research programs. The invention of the pulsed laser {MAIMAN \Rightarrow 1960} enables researchers to deposit enormous power densities in very small volumes, thus allowing the generation of very strong shock waves at microscopic dimensions. On the other hand, the discovery of the Earth's bow shock {AXFORD & KELLOGG \Rightarrow 1962; \Rightarrow Fig. 4.12–D} first illustrates the enormous dimensions shock waves can assume in nature. This discovery also stimulates interest in the generation of the solar wind and in the physics of the corona of the Sun, our closest star. Furthermore, it prompts the question of whether other planets of the Solar System are also surrounded by bow shocks. The question of the existence of a *heliospheric termination shock* is the subject of present investigations {Voyager 1 & 2 \Rightarrow 2003}. The discoveries of quasars {MATTHEWS & SANDAGE \Rightarrow 1960; M. SCHMIDT \Rightarrow 1963} and pulsars {BELL & HEWISH \Rightarrow 1967} using optical, radio and X-ray astron-

omy initiate discussions on the role of shock phenomena of galactic dimensions, such as the origin of cosmic rays and possible mechanisms of their production in supernovae by high Mach number shock waves {BAADE & ZWICKY \Rightarrow 1934; GINZBURG & SYROVATSKII \Rightarrow 1961; ISEE Program \Rightarrow 1977; HESS \Rightarrow 2004}.

Documentation and Dissemination. Over the past five decades, shock wave physics and detonation physics have grown into huge fields of their own: new results in these fields are published not only in a large number of textbooks, technical reports and patents, but also in an increasing number of specific journals addressing almost every offshoot of these disciplines. For example, journals covering nonlinear acoustics, high-speed aerodynamics, gas dynamics, supersonic combustion, detonation, high-velocity impact, *etc.*, are listed in the CHRONOLOGY and include the following:

- ▶ *Journal of the Acoustical Society of America (JASA)* { \Rightarrow 1929};
- ▶ *Combustion and Flame* { \Rightarrow 1954};
- ▶ *Astronautica acta* { \Rightarrow 1955};
- ▶ *AIAA Journal* { \Rightarrow 1963};
- ▶ *Combustion, Explosion, and Shock Waves* { \Rightarrow 1965};
- ▶ *Shock and Vibration Digest* { \Rightarrow 1969};
- ▶ *Propellants, Explosives, Pyrotechnics* { \Rightarrow 1976};
- ▶ *International Journal of Impact Engineering* { \Rightarrow 1983};
- ▶ *Experiments in Fluids* { \Rightarrow 1983};
- ▶ *Physics of Fluids A* { \Rightarrow 1989}; and
- ▶ *Shock Waves* { \Rightarrow 1990}.

In addition, a considerable number of conferences dedicated to shock wave physics and shock effects have been organized, *e.g.*, the

- ▶ Symposia on Shock & Vibration {1947};
- ▶ Symposia on Cosmical Gas Dynamics { \Rightarrow 1949};
- ▶ Biennial Gas Dynamics Symposium {VON KÁRMÁN \Rightarrow 1955};
- ▶ Int. Symposia on Shock Tubes { \Rightarrow 1957};
- ▶ Int. Symposia on Rarefied Gas Dynamics { \Rightarrow 1958};
- ▶ Meetings of the Aeroballistic Range Association, ARA { \Rightarrow 1961};
- ▶ Symposia Transsonica { \Rightarrow 1962};
- ▶ AIRAPT International High Pressure Conferences { \Rightarrow 1965};
- ▶ Conferences on Shock Metamorphism of Natural Materials { \Rightarrow 1966};
- ▶ Int. Symposia on Military Applications of Blast Simulation, MABS { \Rightarrow 1967};
- ▶ Int. Colloquia on Gas Dynamics of Explosions { \Rightarrow 1967};

- ▶ Oxford Conferences on Mechanical Properties of Materials at High Rates of Strain { \Rightarrow 1974};
- ▶ APS Conferences on Shock Waves in Condensed Matter { \Rightarrow 1979};
- ▶ Int. Mach Reflection Symposia { \Rightarrow 1981};
- ▶ Int. Conferences on Mechanical and Physical Behavior of Materials under Dynamic Loading {DYMAT \Rightarrow 1985; EURODYMAT 1994};
- ▶ High Velocity Impact Symposia, HVIS { \Rightarrow 1986}; and
- ▶ crashMat Conferences { \Rightarrow 2001}.

Other conferences, particularly those devoted to high-speed photography and diagnostics, traditionally serve as an important vehicle for exchanging new ideas and results among researchers working worldwide in shock physics, detonics and supersonic combustion research, such as the International Congresses on High-Speed Photography (& Photonics) { \Rightarrow 1952} and the International Symposia on Flow Visualization { \Rightarrow 1977}.

2.4.3 AERIAL WAVES OF FINITE AMPLITUDE: A CHALLENGE FOR MATHEMATICIANS

*The particles on the crest are themselves moving in the direction of the wave motion, and with a velocity which becomes greater and greater (for the particles which happen to be on the crest) as the wave approaches the shore. It is evident that the limit to these circumstances is, that the front of the wave becomes as steep as a wall, while the uppermost particles are moving towards the shore and the lowermost from the shore; that the former, therefore, will tumble over the latter; and this is the motion of a surf.*²¹⁹

Sir George B. AIRY
University of Cambridge
Cambridge 1845

Surprisingly, the discontinuity problem closely associated with a shock wave was successfully tackled by neither experimentalists nor philosophers, but rather by mathematical physicists. The French engineer and mathematician Emile JOUGUET²²⁰ wrote, “The shock wave represents a phenomenon of rare peculiarity such that it has been discovered by the pen of mathematicians, first by RIEMANN, then by HUGONOT. The experiments did not happen until afterwards.” RIEMANN { \Rightarrow 1859} and HUGONOT { \Rightarrow 1887}, how-

²¹⁹ G.B. AIRY: *Tides and waves*. In: (E. SMEDLEY, Hugh J. ROSE, and Henry J. ROSE, eds.) *Encyclopaedia Metropolitana*. B. Fellowes, Oxford & Cambridge, vol. 5 (1845), §298, p. 301, and §249, p. 314.

²²⁰ E. JOUGUET: *Résumé des théories sur la propagation des explosions*. La Science Aérienne 3, No. 2, 138-155 (1934).

ever, were not the only pioneers. As shown in Fig. 2.15 and in the CHRONOLOGY, they had a surprisingly large number of predecessors who substantially contributed to this new field, thus paving the way for a gradual increase in our understanding of discontinuous wave propagation.

Water Waves. Wave phenomena on the surface of water – ranging from waves of small amplitude (*ripples*) to those of large amplitude (*tidal bores*, *tsunamis*) – have fascinated man since the earliest times. The unsteady nature of a tidal bore, with its well-defined front, is a spectacular event that occurs periodically in many estuaries of large rivers around the world. It is certainly the most illustrative demonstration of a propagating discontinuity, considering its enormous kinetic energy and huge destructive power, and that it advances with a roaring sound several times faster than walking speed and moves up the river for many miles.

The first steps toward the development of a theory of tides and waves can be ascribed to Sir Isaac NEWTON's theory²²¹ of the equilibrium tide, in which he investigated the forces that raise tides, and to Daniel BERNOULLI's theory²²² of ocean tides (1740). These studies were considerably extended by numerous French contributions, such as from Pierre-Simon DE LAPLACE²²³ (1790), Joseph L. DE LAGRANGE²²⁴ (1811–1815), Augustin L. CAUCHY²²⁵ (1815), and Siméon D. POISSON²²⁶ (1815–1816). Originally, the mathematicians CAUCHY and POISSON were dissatisfied with the fact that their predecessors had only dealt with the problem of preformed waves. Independently, they discussed the problem of the “generation of a wave,” produced when the surface of deep water is disturbed momentarily. The solution of their theory is the so-called “Cauchy-Poisson wave”

{CAUCHY \Rightarrow 1815; POISSON \Rightarrow 1815}, a wave in which the wavelength increases with the distance from the disturbance. Wave gauge records obtained in 1952 from tsunamis originating from a series of violent seaquakes in Japan showed close agreement with the theory of the Cauchy-Poisson wave, thus confirming that this wave type actually does exist in nature {UNOKI & NAKANO \Rightarrow 1952}.

AIRY, CHALLIS, STOKES, Lord RAYLEIGH, JOUGUET, and LAMB – to mention only a few of the early contributors to hydrodynamics and shock wave physics – started from investigations of water wave phenomena and then turned to shock waves. Obviously, for mathematicians the analogy between the equations of the shallow water theory and the fundamental differential equations describing a one-dimensional compressible flow in air was particularly striking. Since discontinuous wave propagation of water waves – contrary to shock waves in gases – can easily be followed by the naked eye, even on a laboratory scale, no expensive high-speed cameras and special high-intensity short-duration light sources were necessary. In so-called “water table experiments,” the benefits of this technique were studied in great detail {PREISWERK \Rightarrow 1938; H.A. EINSTEIN \Rightarrow 1946; CROSSLEY JR. 1949}.

However, these classical studies also revealed some limitations of this method. The approximate theory of waves of finite amplitude propagating in shallow water is not a linear one, because the wave crests are higher above the mean water line than the troughs are below the mean water line. James J. STOKER,²²⁷ a U.S. applied mathematician at the Courant Institute in New York who specialized in using mathematical analysis to determine water flow and flood waves of rivers and large reservoirs, wrote in his textbook *Water Waves*: “The theory is often attributed to STOKES [1845, \Rightarrow 1849] and AIRY [\Rightarrow 1845], but was really known to DE LAGRANGE [\Rightarrow 1781]. If linearized by making the additional assumption that the wave amplitudes are small, the theory becomes the same as that employed as the mathematical basis for the theory of the tides in the oceans. In the lowest order of approximation, the nonlinear shallow water theory results in a system of hyperbolic partial differential equations, which in important special cases can be treated in a most illuminating way with the aid of the method of characteristics.”

STOKER attributed this analogy to Dmitri RIABOUCHINSKY { \Rightarrow 1932}, a Soviet aerodynamicist renowned for constructing Russia's first important wind tunnel in 1904. But prior to him, the French engineer and mathematician Emile JOUGUET

²²¹ See Sir Isaac NEWTON { \Rightarrow 1687}; *Principia*, Book I, Prop. 66, and Book III, Prop. 24.

²²² In the year 1740, the *Académie Royale des Sciences de Paris* asked the following question “Quelle est la cause du flux et du reflux de la mer?” The prize was awarded for four memoirs, submitted by R.P.A. CAVALLERI, D. BERNOULLI, L. EULER, and C. MACLAURIN. BERNOULLI's contribution [see *Prix* 1740, pp. 55–191] is the longest in the volume, and after his *Hydrodynamica* it is the longest of all his works. The problem of tides must have occupied him for a long time.

²²³ P.S. DE LAPLACE: *Mémoire sur le flux et le reflux de la mer*. *Mém. Acad. Roy. Sci.* (1790–1797), pp. 45–181.

²²⁴ J.L. DE LAGRANGE: *Mécanique analytique*. Courcier, Paris (1811–1815), vol. II.

²²⁵ L. CAUCHY: *Mémoire sur la théorie de la propagation des ondes à la surface d'un fluide pesant d'une profondeur indéfinie* [1815]. *Mém. Sav. Étrang.* I, 3–312 (1827). • In 1816, CAUCHY won a contest held by the French Academy on the propagation of waves at the surface of a liquid. His solution became a milestone in the evolution of hydrodynamics.

²²⁶ D.S. POISSON: *Mémoire sur la théorie des ondes* [1815]. *Mém. Acad. Sci. Inst. France* I, 71–186 (1816).

²²⁷ See STOKER { \Rightarrow 1957}, pp. x–xi, 25–32.

{ \Rightarrow 1920}, then one of the leading shock wave pioneers and today better known as one of the intellectual fathers of the first detonation theory, had already discussed the similarity between shooting channel flow and supersonic compressible flow. On the other hand, JOUGUET was stimulated by his countryman Jean Baptiste BÉLANGER { \Rightarrow 1828}, a professor of mechanical engineering who first theoretically studied the propagation of hydraulic jumps in open water channels. In the 1840s, the English mathematician and astronomer George B. AIRY was the first to work out a theory of river tides {AIRY \Rightarrow 1845}. He also first predicted that the propagation velocity of a tidal wave is amplitude-dependent, and concluded that “a wave of this type cannot be propagated entirely without change of profile, since the speed varies with height” {AIRY \Rightarrow 1845}.

Approach to Shock Waves. The theoretical approach to treating shock waves can be traced back as far as to the *Principia* {Sir NEWTON \Rightarrow 1687}, in which sound propagation in a fluid is explained by the transport of impulses between individual particles – an illustrative model which stimulated not only the genesis of thermodynamics, but was also resumed by some early shock pioneers and even by modern researchers { \Rightarrow Fig. 4.4–A}. Assuming, erroneously, that sound is an isothermal process, Sir Isaac NEWTON made a crude calculation of the sound velocity in air. The great French mathematician, astronomer, and physicist Pierre-Simon DE LAPLACE { \Rightarrow 1816}, noticing a discrepancy of almost 20% between NEWTON’s theoretical result and preexisting measured data {MERSENNE \Rightarrow 1636 & 1644}, improved the theory by assuming that sound is an *adiabatic* process – a term coined by RANKINE { \Rightarrow 1859}. Prior to this, POISSON { \Rightarrow 1808}, stimulated into working on this subject by DE LAPLACE, had mathematically tackled the sound velocity problem in a paper published in the *Journal de l’Ecole Polytechnique* (Paris). Under the heading *Mouvement d’une ligne d’air dans le cas où les vitesses des molécules ne sont pas supposées très-petites* (“One-dimensional Movement of Air in the Case that the Velocities of the Molecules are No Longer Very Small”), he also approached the basic question of how to solve the wave equation in the case of finite amplitude, thus laying the foundations for the first shock wave theory { \Rightarrow Fig. 2.17}. It is worth noting that this happened at a time when an experimental verification of such discontinuities, propagating invisibly through the air as a wave of condensation, was still pending.

POISSON’s early approach, first resumed by the English astronomer James CHALLIS { \Rightarrow 1848}, was extended in the following decades by numerous researchers in England, France and Germany {AIRY \Rightarrow 1848; STOKES \Rightarrow 1848 & 1849; RANKINE \Rightarrow 1858 & 1870; EARNSHAW \Rightarrow 1858, 1859 & 1860; RIEMANN \Rightarrow 1859; CHRISTOFFEL \Rightarrow 1877; HUGONOT \Rightarrow 1885–1887; TUMLIRZ \Rightarrow 1887; BURTON \Rightarrow 1893; HADAMARD \Rightarrow 1903; WEBER \Rightarrow 1901; DUHEM 1901–1909; JOUGUET 1901–1910; LUMMER \Rightarrow 1905; ZEMPLÉN \Rightarrow 1905; Lord RAYLEIGH \Rightarrow 1910; G.I. TAYLOR \Rightarrow 1910; *etc.*}. However, the transition to present-day shock wave theory, largely a result of many more advanced contributions made by international researchers, was not straightforward. We often take this knowledge for granted, ignoring the partially impetuous disputes²²⁸ and cumbersome struggles that it took to achieve our current understanding of the shock wave riddle. Details of this gradual process of understanding may be found in the CHRONOLOGY.

Motivations. In this context, some remarks concerning the motivation for tackling the problem of shock waves seem to be worth mentioning here:

- ▶ AIRY, CHALLIS, and JOUGUET first studied tidal bores out of mathematical curiosity.
- ▶ In 1834, John S. RUSSELL { \Rightarrow 1834}, an English naval architect best known for his research into ship design, chanced upon the *great solitary wave* (or *wave of translation*) – a wave phenomenon consisting of a single crest that arises when a single negative bore immediately follows an equal positive bore. In a wave of translation, the water particles advance with the wave and do not return to their original position.
- ▶ RUSSELL was also the first to observe a curious wave reflection phenomenon {E. MACH & WOSYKA \Rightarrow 1875; \Rightarrow Fig. 4.13–A} which was later termed the *Mach effect* (or *Mach reflection effect*) {VON NEUMANN \Rightarrow 1943}.
- ▶ In 1845, the Rev. Samuel EARNSHAW, an English mathematician, began to treat bores in more depth theoretically. A few years later, after he had a crucial experience with thunder {EARNSHAW \Rightarrow 1851}, he turned his attentions to this subject, before finally investigating airborne waves of finite amplitude.

²²⁸ For example, see the disputes between EULER and DE LAGRANGE {EULER \Rightarrow 1759}, PARRY and GALBRAITH {PARRY \Rightarrow 1824/1825}, CHALLIS and STOKES {STOKES \Rightarrow 1848}, CHALLIS and AIRY {CHALLIS \Rightarrow 1848}, EARNSHAW and LE CONTE {LE CONTE \Rightarrow 1864}, and Lord RAYLEIGH and STOKES {Lord RAYLEIGH \Rightarrow 1877}.

- ▶ Bernhard RIEMANN, the famous German mathematician, took a keen interest in the nature of *Luftwellen von endlicher Schwingungsweite* (“Aerial Waves of Finite Amplitude”). This interest did not arise from pure mathematical curiosity, but rather was stimulated by the German physicist Hermann VON HELMHOLTZ. In 1856, while studying combination tones, VON HELMHOLTZ had discovered the unusual phenomenon that the sounding of two musical tones of high intensity results in the appearance of a sum frequency as well as a difference frequency. VON HELMHOLTZ attributed the presence of these combination tones to the nonlinearity of the ear. However, the British physics professor Arthur W. RÜCKER²²⁹ and his collaborator Edwin EDSER were the first to prove that the interaction actually occurs in the medium, by exciting a tuning fork at the sum frequency.
- ▶ William J.M. RANKINE in England and Pierre-Henri HUGONIOT in France approached the shock wave phenomenon from a thermodynamics viewpoint.
- ▶ The British physicist Lord RAYLEIGH, who wrote the first textbook on acoustics, became interested in aerial shock waves due to his curiosity about the physical conditions at the shock front.
- ▶ The German mathematician Heinrich M. WEBER treated shock waves as a mathematical problem in order to find solutions for various types of partial differential equations. He later edited RIEMANN’s lectures on mathematical physics and extended his own theoretical studies of shock waves through numerous examples and comments.

Superposition of Shock Waves. From a mathematical physics perspective, shock waves are nonlinear problems because the equations of state, $p(\rho)$, are usually nonlinear. For all normal fluids, the equation of state produces a plot that curves concave upwards in the (p, ρ) -plane, so disturbances in pressure $p > p_0$ and consequently in density $\rho > \rho_0$ propagate with supersonic velocity because of $c = (dp/d\rho)^{1/2} > c_0$ {⇒ Fig. 2.1}. Here p_0 and ρ_0 are the pressure and density of the undisturbed fluid, respectively.

The German theoretical physicist Werner HEISENBERG²³⁰ also showed a recurrent interest in nonlinear problems related

to fluid dynamics and shock waves. In two papers – one published in 1924 on vortex motion entitled *Nichtlineare Lösungen der Differentialgleichungen für reibende Flüssigkeiten* (“Nonlinear Solutions of Differential Equations for Frictional Liquids”), and the other published in 1953 on meson production entitled *Theorie der Explosionsschauer* (“Theory of Explosion Showers”), in which he treated mesons (a group of subatomic particles) as a shock wave problem – he pointed out the general difficulties of obtaining physically meaningful solutions for nonlinear equations. Obviously, in the case of shock waves the behavior of the substance at very small dimensions becomes important. Fortunately, as he pointed out, in gas dynamics it is often not necessary to go into the microscopic details: in order to determine the course of the shock wave, it is instead enough to describe the irreversible processes in the shock through an increase in entropy.

The superposition of shock waves is itself another nonlinear phenomenon. This “nonlinear interaction” of “nonlinear processes” in the shock wave is, therefore, a very complex phenomenon. Consequently, the resulting shock pressure in the region of interaction is not the arithmetic sum of the two incident pressures (as in the acoustic case): it is always larger, and depends on the shock strength and the angle at which the two shock fronts interact with each other. In the case of the *Mach effect* {E. MACH & WOSYKA ⇒ 1875}, a third shock wave – the *Mach shock* – is generated besides the *incident shock* and the *reflected shock*. Depending on the interaction geometry, this Mach shock also assumes different names {⇒ Fig. 2.14}: an oblique reflection of a (planar or curved) shock front at a solid boundary produces the so-called “Mach stem,” while an oblique interaction of two propagating shock waves of equal strengths and geometries (either planar or curved) produces a symmetric phenomenon – termed a *Mach disk* (or *Mach bridge*).

Since the establishment of the four basic types of oblique shock wave reflection {WHITE ⇒ 1951}, a number of special cases of single and double Mach reflection have been observed and named {⇒ Fig. 2.14}. In 1985, a common nomenclature was proposed in order to avoid confusion and to improve communications between investigators²³¹ – a difficult goal which has so far been only partially realized.

²²⁹ See their paper *On the objective reality of combination tones*. Proc. Phys. Soc. (Lond.) **13**, 412-430 (1895).

²³⁰ W. HEISENBERG: *Nonlinear problems in physics*. Phys. Today **20**, 27-33 (May 1967).

²³¹ G. BEN-DOR and J.M. DEWEY: *The Mach reflection phenomenon: a suggestion for an international nomenclature*. AIAA J. **23**, 1650-1652 (1985).

2.4.4 SHOCK WAVES IN GASES: FIRST EXPERIMENTAL PROOFS OF THEIR EXISTENCE

It seems as if the locus of interference between the two original [shock] waves has become the source of a third wave which, during propagation, interferes with the two original ones. This V-propagation can be explained as an area of superposition of the two waves which is attributed to a larger propagation velocity – this locus can be understood as a wave in the wave; i.e., as a second wave which propagates with an excessive velocity within the first wave. This interpretation fully agrees with the quantitative results of my third and fourth work.²³²

Ernst MACH
Karl-Ferdinand-Universität
Prague 1878

A gas is a collection of molecules separated by distances so large that most of the time the molecules interact only weakly with each other. The brief periods during which the molecules interact strongly are considered to be *collisions*.

Shock waves can be regarded in one sense as the modern version of percussion. However, compared to classical percussion dealing with tangible bodies, shock transmission occurs on a microscopic level in a gas: the momentum is transmitted via innumerable individual collision processes from one molecule (or atom) to another. For example, in a monatomic gas it takes only a few collisions to adjust to the different equilibrium states between the upstream and downstream sides of a shock wave – i.e., a shock front is only a few mean free paths thick. The unique behavior of a traveling shock can best be illustrated to the novice using the various chain percussion models that have been proposed in the literature. Some of them are shown in Fig. 4.4–D.

The rapid development of experimental shock wave physics started with studies of gases usually performed for the following reasons:

- ▶ In the 17th century, the elastic nature of air – popularized by Robert BOYLE as “the spring of the air” – was studied experimentally and was also used in practice. Prominent examples include various constructions of the so-called “air gun” or “wind gun” {GUTER ⇨ 1430; BOYLE ⇨ 1647; ⇨ Fig. 4.2–I} in which the force employed to propel the bullet is the elasticity of compressed atmospheric air, and pneumatic lighters {⇨ Fig. 4.2–K}, which impressively demonstrate the adiabatic properties of quickly-compressed air. The

first step towards a scientific theory of shock waves was the determination of the isothermal equation of state of a gas {BOYLE & TOWNLEY ⇨ 1660}.

- ▶ The relatively low velocity of sound in air in comparison to that in a liquid or solid (it is, for example, smaller by factors of about 5 and 20 in water and iron, respectively) was advantageous for 19th-century experimentalists, when high-speed diagnostics were still in their infancy, and the smallest time resolution achievable was mostly limited to the medium micro-second regime.
- ▶ All three optical standard methods – schlieren, shadowgraphy and interferometry – are light transmission techniques; i.e. they require a transparent medium and are therefore ideally suited for studies in gases.
- ▶ In practice, the majority of shock wave applications still occur in air.

The Roots of Gas Dynamics. Shock waves in gases fall under the remit of the wide field of *gas dynamics* or *compressible flow*. The first memoir on this subject was apparently published by the Polish physicist Marian SMOLUCHOWSKI {⇨ 1903}. He termed this branch of fluid dynamics *aerodynamics*. In the same year, the Hungarian-Swiss engineer Aurel STODOLA {⇨ 1903} first treated the thermodynamics of high-speed flows in his classical textbook *Die Dampfturbinen und die Aussichten der Wärmekraftmaschinen* (“Steam Turbines, With an Appendix on Gas Turbines and the Future of Heat Engines”). The first handbook articles on gas dynamics, which also emphasized shock wave phenomena, were published by Felix AUERBACH (1908), Ludwig PRANDTL (1913), Jakob ACKERET (1927), Adolf BUSEMANN (1931), and Albert BETZ (1931) {AUERBACH ⇨ 1908}. In the following years, important contributions to the fundamental treatment of gas dynamics were made in England by Geoffrey I. TAYLOR²³³ and John W. MACCOLL, and in Germany by Robert SAUER.²³⁴

The roots of gas dynamics can be traced back to early attempts to calculate the velocity of sound in air {Sir NEWTON ⇨ 1687; BIOT ⇨ 1802; DE LAPLACE ⇨ 1816; Bureau des Longitudes ⇨ 1822; POISSON ⇨ 1823}. It was recognized early on that a long baseline is needed to measure the sound velocity in order to compensate for the limited accuracy of the clocks available at the time {MERSENNE ⇨ 1636; CASSINI

²³² This is Ernst MACH’s ingenious interpretation of “Mach reflection.” See his paper *Über den Verlauf der Funkenwellen in der Ebene und im Raum*. Sitzungsber. Akad. Wiss. Wien 77 [Abth. II], p. 819 (1878).

²³³ G.I. TAYLOR and J.W. MACCOLL: *The mechanics of compressible fluids*. In: (W.F. DURAND, ed.) *Aerodynamic theory*. Springer, Berlin, vol. 3 (1935), chap. H, pp. 209–250.

²³⁴ R. SAUER: *Theoretische Einführung in die Gasdynamik*. Springer, Berlin (1943).

DE THURY ET AL. \Rightarrow 1738}. This method, however, was not directly transferable to the crucial test of whether waves of intense sound propagate faster than the velocity of sound: since the pressure rapidly decreases with the distance from the source, the region of supersonic velocity is limited to the near-field of the explosion source.

First Studies of Intense Air Waves. The first attempt to mathematically predict the velocity of sound {Sir NEWTON \Rightarrow 1687} had shown a considerable discrepancy between theory and measurement, and subsequent generations of naturalists attempted to develop a general mathematical theory of sound that was capable of correctly predicting the velocity of sound as a function of the density, temperature and humidity of the air, as well as the pitch and intensity of the sound.

Experiments made by Jean-Baptiste BIOT { \Rightarrow 1809} in France and William Henry BESANT { \Rightarrow 1859} in England provided evidence that whatever the pitch and loudness, all musical sounds are transmitted with precisely the same velocity. Some researchers, extrapolating these results without hesitation to violent sounds in general, denied any effects of sound intensity on the velocity of sound at all {LE CONTE \Rightarrow 1864}. On the other hand, there was also experimental evidence that the velocity of sound does indeed depend on intensity. In order to eliminate all possible influences of humidity on sound propagation, the English arctic explorers William E. PARRY, Henry FOSTER and James C. ROSS { \Rightarrow 1824/1825} performed measurements of the velocity of sound at very low temperatures in the North Polar region; *i.e.*, in perfectly dry air. They observed by chance the curious phenomenon that the report of a gun was heard at their furthest station *before* the command to fire { \Rightarrow Fig. 2.10–D}. This suggested that intense air waves (here the muzzle blast) travel more quickly than weak air waves (here the commander’s voice). The Rev. Samuel EARNSHAW { \Rightarrow 1858 & 1864} considered their observation to be important proof of his mathematical theory of sound.

Evidence that the velocity of sound depends on its intensity was also observed in France. The skillful experimentalist Henri REGNAULT { \Rightarrow 1863}, then widely known for his sophisticated test methods and careful measurements, originally intended to measure sound velocities in various gases and liquids. In order to get a long baseline, he performed his experiments in the public sewage channels and gas pipelines of Paris, which advantageously confined the sound to two dimensions. To secure sufficient sound intensity at the receiver station, he generated the sound at the tube entrance with small amounts of explosives { \Rightarrow Fig. 2.10–F}. He was

initially unaware that in doing so he introduced shock (blast) waves rather than sound waves into his measurement method. His remarkable results, published in various international journals but now almost forgotten, obviously quantitatively proved the existence of supersonic velocities for the first time and certainly must have encouraged contemporaries from other countries to tackle this subject further.

Mach Reflection. Ernst MACH, who in the period 1867–1895 held the chair of experimental physics at the German *Karl-Ferdinand-Universität* (“Charles University”) in Prague, was interested in physical and physiological acoustics. He was supported by a team of coworkers, which later also included his oldest son Ludwig MACH, and he had the opportunity to systematically continue his research in this particular field through a period of almost 28 years, which was most unusual in the research scene of the 19th century. Curiously enough, E. MACH began his gas dynamic studies with research into one of the most difficult subjects in shock wave physics, the oblique interaction of shock waves {E. MACH & WOSYKA \Rightarrow 1875; \Rightarrow Figs. 4.5–D & 4.13–C}. This subject presented a particularly difficult challenge to researchers during the evolution of gas dynamics. Later termed the *Mach effect* by the Hungarian-born U.S. mathematician John VON NEUMANN { \Rightarrow 1943}, this interaction is a complex nonlinear superposition phenomenon and still remains a fascinating subject for thorough experimental and theoretical research {Mach Reflection Symposium \Rightarrow 1981}.

The Mach effect is characterized by a triple point at which three branches of shock waves intersect: the incident shock wave, the reflected shock wave, and a third shock wave – the *Mach stem* – behind which the pressure is larger than that behind the incident and reflected shock wave { \Rightarrow Fig. 2.14}. This curious so-called “three-shock problem” {VON NEUMANN \Rightarrow 1943} was first studied systematically in shock tube experiments at Princeton University under the guidance of the physics professor Walker BLEAKNEY {BLEAKNEY & TAUB \Rightarrow 1949}. When he applied stronger incident shock waves, Donald R. WHITE { \Rightarrow 1951}, one of BLEAKNEY’s coworkers, observed a new, very complex shock interaction geometry with two triple points { \Rightarrow Figs. 2.14(d) & 4.13–D}. Later, this type of shock wave interaction was termed *double Mach reflection* in order to differentiate it from the more common one-triple-point geometry, which was termed *single Mach reflection*.

Richard COURANT and Kurt O. FRIEDRICHs, when discussing the reflection of shock waves in their book *Supersonic Flow and Shock Waves* { \Rightarrow 1948}, only differentiated between three types of Mach reflection (MR): (i) *direct MR*

when the triple point (TP) moves away from the reflecting surface; (ii) *stationary MR* when TP moves parallel to the reflecting surface; and (iii) *inverted MR* when TP moves towards the reflecting surface. They also proposed the term *λ -configuration* instead of *Mach reflection*, which, however, was not adopted by others.

Particularly in gas dynamics, Mach reflection is an almost omnipresent phenomenon and one that can manifest itself in a number of different wave configurations. This created a wealth of new special terms, some of which were placed in a more recent classification scheme. A brief historical review of this particular branch of shock wave physics was given by Gabi BEN-DOR,²³⁵ a shock physics professor at Ben-Gurion University of the Negev.

The Mach effect exists in all states of matter. In 1842, the Scottish naval engineer John S. RUSSELL { \Rightarrow 1842} studied the reflection of hydraulic jumps at a solid boundary, during which he observed incidentally Mach reflection²³⁶ (*i.e.*, before even Ernst MACH in 1875); this achievement is barely known in the shock physics community. RUSSELL documented his observation using a pen-and-ink drawing { \Rightarrow Fig. 4.13–A} because high-speed photography {TALBOT \Rightarrow 1851; MADDIX \Rightarrow 1871} had not yet been established. Later, this unusual wave interaction phenomenon was also photographed in nature by the Englishman Vaughan CORNISH { \Rightarrow 1910} and published in his book *Waves of the Sea and Other Water Waves* { \Rightarrow Fig. 4.1–M}.

After the discovery of Mach reflection in air {E. MACH & WOSYKA \Rightarrow 1875}, there was speculation about whether this effect might also exist in other states of matter. In shock wave studies performed in the United States during World War II, it was shown that Mach reflection also exists in a liquid (water) {SPITZER & PRICE \Rightarrow 1943}. Later, it was shown in the Soviet Union that Mach reflection also occurs when detonation waves generated in a triangular prism constructed from a solid high explosive interact obliquely {E.A. FEOKTISTOVA \Rightarrow 1960}. Soviet physicists also first experimentally demonstrated the existence of Mach reflection in solids such as aluminum and iron {AL'TSHULER ET AL. \Rightarrow 1962}.

First Laboratory-Scale Supersonic Studies. Although supersonic aerodynamics was not a completely new branch of fluid dynamics by the 1870s – its validity had already been

proven experimentally {ROBINS \Rightarrow 1746; HUTTON \Rightarrow 1783; PARRY \Rightarrow 1824/1825; REGNAULT \Rightarrow 1863} – Ernst MACH initiated a scientific investigation of shock waves performed at the laboratory scale that introduced the use of high-speed visualization with microsecond resolution. Based on his numerous fundamental contributions to shock waves, he is now generally considered to be the father of supersonics. After his discovery of “Mach reflection,” he proved experimentally, together with his student Jan SOMMER, that a shock wave does indeed propagate at supersonic velocities, but it rapidly approaches the velocity of sound as the distance from the source increases {E. MACH & SOMMER \Rightarrow 1877}, thus confirming on a laboratory scale REGNAULT’s previous results from full-scale propagation studies.

MACH’s most famous experiments, however, were certainly his ballistic studies. Together with Peter SALCHER, an Austrian physicist and professor at the Austrian-Hungarian Marine Academy in Rijeka [now Fiume, Croatia], he first showed that a projectile flying supersonically produces a shock wave with a roughly hyperbolic shape which is fixed to the projectile – the “head wave” or “bow wave” [German *Kopfwelle* or *Bugwelle*], known in France as “l’onde balistique” {E. MACH & SALCHER \Rightarrow 1886; \Rightarrow Figs. 4.6–E to G}. This curious wave phenomenon had already been predicted by the Austrian physicist Christian A. DOPPLER { \Rightarrow 1847} using a simple graphical method { \Rightarrow Figs. 4.6–B, C} based upon the application of the Huygens principle {HUYGENS \Rightarrow 1678; \Rightarrow Fig. 4.6–A}. However, there were no experimental diagnostic means at DOPPLER’s disposal to prove his ingenious concept. The discovery of the supersonic head wave immediately prompted great interest in military circles, since fundamental research in this area could result in a better understanding of aerodynamic drag and ultimately projectile geometries with minimum drag – thus significantly increasing the effective ballistic ranges of fire arms and improving the theoretical prediction of trajectories.

These pioneering experimental investigations performed by Ernst MACH and his team – together with theoretical studies performed in England, France and Germany – resulted in a basic knowledge of supersonic flows in the 1880s. Practical aerodynamics, however, was still in its infancy, and the first flight of man {VON LILIENTHAL \Rightarrow 1891} had not yet been achieved.

The ballistic head wave strongly reminds one of the bow wave generated by an object moving through water. However, there is a significant difference: while in gas dynamics the conical angle decreases as the speed of the object increases, this is not the case with the wake generated by a ship moving through water { \Rightarrow Fig. 4.6–D}. All objects moving

²³⁵ G. BEN-DOR: *Oblique shock wave reflections*. In: (G. BEN-DOR ET AL., eds.) *Handbook of shock waves*. Academic Press, New York, vol. 2 (2001), pp. 67–179.

²³⁶ The author owes this reference to Prof. Manuel G. VELARDE, a fluid physicist at the Instituto Pluridisciplinar of the Universidad Complutense de Madrid, Spain.

through water have a pseudo-effective Mach number of 3, so long as the water is deep compared to the wavelength of the waves produced, the course of the ship is straight, and its speed is constant.²³⁷ Curiously enough, none of the famous European marine painters of previous centuries had ever reproduced this striking bow wave phenomenon, although it can be clearly observed with the naked eye.

Studies of Nozzle Outflow. It appears that studies of the exhaust of compressed gas from an orifice originated from malfunctions or imperfect construction of the safety valve. This simple device was invented by the Frenchman Denis PAPIN and used by him in his *steam digester*, the first pressure cooker {PAPIN \Rightarrow 1679; \Rightarrow Fig. 4.7–A}. With the advent of the first steam engines in the early 18th century, such valves – which initially only consisted of a hole in the boiler wall covered by a plate loaded with a weight – were often applied. However, to avoid the need to use large weights, these valves were often made too narrow to be able to vent dangerous overpressures quickly, resulting in steam-boiler explosions that often produced many casualties and a great deal of material damage { \Rightarrow Fig. 4.21–A}. Boiler explosions were believed to be a complex chain of different causes {ARAGO \Rightarrow 1830; AIRY \Rightarrow 1863}. Eager attempts to avoid them prompted not only engineers but also scientists to undertake detailed studies that became the roots of early supersonic research {VENTURI \Rightarrow 1797; DE SAINT-VENANT & WANTZEL \Rightarrow 1839; FLIEGNER \Rightarrow 1863; NAPIER \Rightarrow 1866; EMDEN \Rightarrow 1903; LORENZ \Rightarrow 1903; FLIEGNER \Rightarrow 1903; PRANDTL \Rightarrow 1908}.

The *Laval nozzle* – a nozzle with a convergent-divergent geometry that was invented by the prominent Swedish industrialist and engineer Carl Gustaf Patrick DE LAVAL and used by him to deliver steam to turbine blades – was the first to permit supersonic flow velocities at its exit {DE LAVAL \Rightarrow 1888}. Thus, the Laval nozzle became an important device in steam turbine engineering { \Rightarrow Figs. 4.7–F, G & 4.8–C}, because it increased the efficiency of steam turbines. In aeronautical engineering, it not only had an enormous impact on rocket engine design { \Rightarrow Fig. 4.7–H}, but it also triggered much supersonic flow research and the development of supersonic wind tunnels { \Rightarrow Figs. 4.8–E & 4.9–A to I}.

These successful studies of outflow phenomena that occur at the exit of a nozzle also stimulated the development of new diagnostic techniques for high-speed visualization, which facilitated the interpretation of supersonic flow phenomena {SALCHER & WHITEHEAD \Rightarrow 1889; L. MACH \Rightarrow 1897; Figs. 4.8–A, B}. Further experimental and theoretic-

cal flow studies of the inside and outside of a Laval nozzle provided a basic knowledge of supersonic flow as a function of nozzle geometry and operational parameters, which stimulated the conception of improved supersonic wind tunnel designs {REYNOLDS \Rightarrow 1883; PRANDTL \Rightarrow 1908; MEYER & PRANDTL \Rightarrow 1908}.

Wind Tunnels. In order to study aerodynamic drag quantitatively, Sir Isaac NEWTON dropped spheres from the dome of St. Paul's Cathedral in London, and from these observations he developed the first theory of aerodynamic drag. Benjamin ROBINS used a whirling-arm device: the object under study was placed at the end of a rotating rod in order to observe the object's rapid passage through the air. Another method was to tow models through still water, since air is a fluid whose behavior is in many ways comparable to that of water.²³⁸ A big step forward in drag research was the direction of a homogeneous high-speed jet of air at scale models in tunnel-like passages – so-called “wind tunnels” – a diagnostic principle that had already been proposed by Leonardo DA VINCI { \Rightarrow 1490s}, but does not appear to have actually been applied by him. Later, the Austrian physicist Peter SALCHER { \Rightarrow 1889}, while visualizing the flow around supersonic projectiles, hit upon the same idea of likewise investigating the inverse case of the flow of air against a body at rest in order to confirm the results already obtained.

Subsonic Wind Tunnels ($M < 0.8$). Subsonic tunnels are the simplest types of wind tunnels. Making use of the Bernoulli theorem {D. BERNOULLI \Rightarrow 1738}, air velocities in this range can use a pipe with a constriction which decreases the pressure and increases the flow velocity {VENTURI \Rightarrow 1797; \Rightarrow Fig. 4.7–D}. The scale model under study is mounted in the contraction in the throat of the tube. The first facilities built according to this concept were rather crude, low-velocity devices used in pioneering British aerofoil studies {WENHAM \Rightarrow 1871; PHILLIPS \Rightarrow 1885; \Rightarrow Fig. 4.7–E}. In the early 1900s, the WRIGHT Brothers { \Rightarrow 1903} also built and used two wind tunnels: the second one, which was more advanced and was driven by a 2-hp gasoline engine, produced a maximum wind velocity of 27 mph (about 12 m/s). Ludwig PRANDTL { \Rightarrow 1907} constructed the first large subsonic wind tunnel with a test cross-section of $2 \times 2 \text{ m}^2$ using a closed-circuit air flow, an operational principle which also proved very useful in the supersonic regime {ACKERET \Rightarrow 1933}.

Transonic Wind Tunnels ($0.8 < M < 1.2$) and Supersonic Wind Tunnels ($1.2 < M < 5$). In addition to low-velocity

²³⁷ R.A.R. TRICKER: *Bores, breakers, waves and wakes*. Am. Elsevier, New York (1965).

²³⁸ The smooth free-surface flow of a liquid (water) over a horizontal bed obeys equations of motion similar to those for the isentropic 2-D flow of a hypothetical gas with specific heat ratio $\gamma = 0.2$. For air this value is 1.4.

aerofoil studies, ballisticians and mathematicians – who had known of the supersonic velocities of small- and large-caliber shots {ROBINS \Rightarrow 1742; EULER \Rightarrow 1745; HUTTON \Rightarrow 1783; MAYEVSKI \Rightarrow 1881} since the 18th century – asked for experimental data on aerodynamic drag and stability, ranging from supersonic muzzle velocities (“ v_0 ”) down to almost zero, in order to allow better predictions of projectile trajectories. Of particular interest was the transonic regime, in which aerodynamic drag changes tremendously { \Rightarrow Fig. 4.14–M}.

Pioneers of supersonic wind tunnel design were confronted with a number of complex problems in this case, for example:

- ▶ to design new nozzle that could produce transonic or supersonic flow in the test section;
- ▶ to develop an appropriate method of supporting the model in the test section in such a way that the flow around the model remains essentially equivalent to that around the model in free flight;
- ▶ to adapt standard methods of optical visualization (e.g., shadow, schlieren, interferometer techniques) to the special requirements of a wind tunnel set-up;
- ▶ to measure the forces on the test model; and
- ▶ to determine the power requirements at various air speeds.

This resulted in some basic design concepts for high-speed wind tunnels, such as continuous closed-circuit tunnels, intermittent indraft tunnels, blow-down tunnels, and pressure-vacuum tunnels.

The first test facilities designed to investigate the supersonic regime were not constructed until the 1920s by the French aeroballisticians Paul LANGEVIN and Constantin CHILOWSKY { \Rightarrow 1918} and Eugène HUGUENARD and Jean André SAINTE-LAGÜE { \Rightarrow Fig. 4.9–A}. The British engineer Sir Thomas E. STANTON adopted the Laval nozzle in the world’s first supersonic wind tunnel, which he called “wind channel.” It was constructed and operated at the National Physics Laboratory (NPL) in Teddington {STANTON \Rightarrow 1921; \Rightarrow Fig. 4.9–B}. In this mini blow-down facility, which had a useful diameter of only 0.8 in. (20.3 mm), supersonic flow velocities of up to a Mach number of $M = 2$ could be achieved.

Supersonic wind tunnels using atmospheric air need drying devices to avoid condensation, a detrimental phenomenon which, producing a dense fog in the tunnel, hinders any optical diagnostics and potentially results in local changes in the Mach number {5th Volta Conf. (PRANDTL) \Rightarrow 1935}. By the late 1930s, a small number of useful supersonic wind tunnels had been built in Europe {STANTON \Rightarrow 1928; ACKERET \Rightarrow 1933; BUSEMANN & WALCHER \Rightarrow 1933; WIESELSBERGER \Rightarrow 1934; CROCCO \Rightarrow 1935; 5th Volta Conf. (ACKERET,

CROCCO) \Rightarrow 1935; HVA Peenemünde \Rightarrow 1939; BETZ \Rightarrow 1939}.

In the United States, the Langley Memorial Aeronautical Laboratory was home to the few transonic and supersonic tunnels owned by the Government before World War II:

- ▶ the 11-in. (27.9-cm)-dia. high-speed tunnel (1928);
- ▶ the 24-in. (61-cm)-dia high-speed tunnel (1934);
- ▶ the 8-ft (244-cm)-dia. high-speed tunnel (Mach 0.5 until 1945, enhanced to Mach 1 in early 1945);
- ▶ the 9-in. (22.9-cm)-dia. supersonic tunnel (designed in 1939, operational in 1942);
- ▶ the 11-in. (27.9-cm)-dia. hypersonic tunnel (designed in 1945, operational in 1947); and
- ▶ the $4 \times 4\text{-ft}^2$ ($122 \times 122\text{-cm}^2$) supersonic pressure tunnel (designed in 1945, operational in 1948).

A $1 \times 3\text{-ft}^2$ ($30.4 \times 91.4\text{-cm}^2$) supersonic tunnel (completed before 1945) also existed at the NACA Ames Laboratory, Moffet Field, CA. Furthermore, three universities (MIT, Cornell and CalTech) owned high-speed wind tunnels.²³⁹ U.S. wind tunnels, ranging from the NACA Wind Tunnel No. 1 (operational in 1920) to advanced wind tunnel technology (up to 1981), were discussed by Donald D. BAALS²⁴⁰ and William R. CORLISS at NASA’s Scientific & Technical Information Branch. Their report contains constructional details and photographs of all of them.

Hypersonic Wind Tunnels ($5 < M < 12$). Hypersonic aerodynamics became important when designing military aircraft, missiles, the space shuttle and other high-speed objects. In order to study and simulate hypersonic flight, new methods of aerodynamic testing were developed. Besides high-speed instrumentation for measuring pressures, densities, forces and temperatures, conventional shadowgraph, schlieren and interferometer techniques were supplemented by new airflow visualization techniques, such as *thermography* { \Rightarrow Fig. 4.18–H}, and *particle tracing*, a method in which the test model is coated with a mixture of oil and fluorescent powder and then exposed to ultraviolet light.

Hypersonic flow velocities of up to almost $M = 9$ {ERDMANN \Rightarrow 1943/1944} were first reached by using a special nozzle design in the large supersonic wind tunnel facility at the *Heeresversuchsanstalt Peenemünde* (“Army Rocket Testing Center Peenemünde”), the main research center for German rocketry during World War II. These studies at Peenemünde had already revealed that realistic simulations

²³⁹ Priv. comm. by Erik M. CONWAY, a visiting historian at NASA Langley Research Center (March 1, 2001).

²⁴⁰ D.D. BAALS and W.R. CORLISS: *Wind tunnels of NASA*. NASA Rept. SP-440, NASA History Office, Washington, DC (1981); <http://www.hq.nasa.gov/office/pao/History/SP-440/cover.htm>.

of hypersonic flows (*i.e.*, of Mach numbers above 5) would require a more sophisticated wind tunnel design. Hypersonic research was not resumed until the late 1940s in the United States {BECKER \Rightarrow 1947; WEGENER \Rightarrow 1951}.

In the following years, a number of hypersonic facilities were constructed using different methods of generating hypersonic flows with large Reynolds numbers, *e.g.*, by modifying conventional hypersonic wind tunnels using a “shroud” technique {FERRI & LIBBY \Rightarrow 1957}, by inventing new testing facilities such as hotshot tunnels, plasma jets and shock tunnels {WITTLIFF, WILSON & HERTZBERG \Rightarrow 1959}, or by using high-velocity ballistic accelerators such as light-gas guns {CROZIER & HUME \Rightarrow 1946; \Rightarrow Fig. 4.11–D}.²⁴¹ A historical perspective of early hypersonic wind tunnel design was given by Julius LUKASIEWICZ,²⁴² a Canadian professor of aerospace engineering at Carleton University in Ottawa, Ontario.

Hypervelocity Wind Tunnels ($M > 12$). Hypervelocity aerodynamics involves the physics of atmospheric reentry. However, there is a fundamental problem with operating wind tunnels at hypervelocities: the ambient temperature in the test section decreases as the Mach number increases until the air liquefies. This would result in inaccurate experimental results. In order to prevent condensation, the stagnation temperature of the air must be very high, *e.g.*, the stagnation temperature in the stilling section must be above 4,700 °C for the ambient temperature in the test section to remain above 0 °C. This requires special heating techniques and vast electrical energy. Examples of hypervelocity tunnels, referred to in the CHRONOLOGY, are the *gun tunnel* or *Stalker tube* {STALKER \Rightarrow 1965} and the *shock tunnel* {WITTLIFF ET AL. \Rightarrow 1959}.

In 1991, Hans GRÖNIG,²⁴³ a German professor of mechanical engineering at the RWTH Aachen, reviewed the development of European hypersonic and hypervelocity wind tunnels used to test models of new space vehicles.

Shock Tubes. The shock tube, invented in France by the physicist and explosives specialist Paul VIEILLE { \Rightarrow 1899} as a by-product of his detonation studies, became the most important measuring and testing device in gas dynamic research. VIEILLE applied the shock tube in order to demonstrate that shock waves generated by the detonation of explosives propagate in essentially the same manner as

shock waves generated by the bursting diaphragm of the high-pressure section that formed one end of his tube. The basic theory for the shock tube was laid down by the German researchers Karl KOBES { \Rightarrow 1910}, Frederick HILDEBRAND { \Rightarrow 1927}, and Hubert SCHARDIN { \Rightarrow 1932}. KOBES and HILDEBRAND had a rather curious approach to gas dynamics: they investigated whether it would be possible to improve the performance of air suction brakes on long railway trains by using shock waves. Their experiments essentially confirmed this hypothesis.

The shock tube – rediscovered during World War II by the U.S. physicist Walker BLEAKNEY and associates at Princeton University {BLEAKNEY \Rightarrow 1946 & 1949}, and further improved by his group through the introduction of a trigger pin to pierce the diaphragm {BLEAKNEY & TAUB \Rightarrow 1949} – soon proved its excellent applicability for quantitatively investigating 1-D propagation and interaction phenomena of shock waves within a wide range of gas dynamic parameters. Furthermore, the shock tube was quickly introduced into other laboratories around the world for studying the interactions of shock waves with scaled architectural structures such as model houses, plants, shelters, and vehicles {BLEAKNEY \Rightarrow 1952; \Rightarrow Fig. 4.5–J}. During the long post-war period of Cold War, such model interactions were of great practical concern because of the constant threat of the use of nuclear blasts against a wide range of civil and military installations.

Special shock tube constructions were produced in the 1960s to simulate the blast waves from nuclear explosions {CULBERTSON \Rightarrow 1970} – a particularly challenging task because higher peak overpressures had to be provided than for chemical explosions, combined with longer pressure durations. In addition, such blast simulators were supplemented with thermal radiation simulators to get a realistic picture of the overall effects of nuclear damage – so-called “synergetic effects” {MORRIS \Rightarrow 1971}. Since the shock tube is also a perfect, low-cost tool for studying supersonic flow patterns over an enormous range of Mach numbers, its use even replaced traditional wind tunnel work to some extent {MAUTZ, GEIGER & EPSTEIN \Rightarrow 1948; BLEAKNEY & TAUB \Rightarrow 1949}. However, the electronic diagnostics used in shock tube facilities must be fast, and were therefore initially more expensive than those in wind tunnels. This delayed wide application of the shock tube for such purposes at first, but the costs of such equipment have since considerably decreased.

The shock tube also proved to be most useful for studying the ignition and detonation behavior of explosive gaseous mixtures {PAYMAN & SHEPHERD \Rightarrow 1937 & 1940; SHEPHERD \Rightarrow 1948}. That the shock tube was also useful for generating

²⁴¹ A. POPE and K.L. GOIN: *High-speed wind tunnel testing*. Wiley, New York *etc.* (1965), pp. 442–460.

²⁴² J. LUKASIEWICZ: *Experimental methods of hypersonics*. M. Dekker, New York (1973), pp. 25–51.

²⁴³ H. GRÖNIG: *Shock tube application: high enthalpy European wind tunnels*. In: (K. TAKAYAMA, ed.) *Proc. 18th Int. Symposium on Shock Waves* [Sendai, Japan, July 1991]. Springer, Berlin *etc.* (1992), vol. 1, pp. 3–16.

high temperatures in gases was first recognized and exploited in high-speed spectroscopic studies by Otto LAPORTE {⇒1953}, a German-born U.S. physicist who first applied reflected shock waves to produce high temperatures in gases. The shock tube was also successfully modified for use in studies of chemical kinetics {GLICK, SQUIRE & HERTZBERG ⇒1957}. The magnetically driven shock tube {KOLB ⇒1957} first allowed Mach numbers in excess of 100 and extended the highest shock temperatures that could be attained up to one million degrees. However, with the advent of high-power pulsed lasers in the 1960s, expectations that this technique would eventually be used to help produce controlled nuclear fusion dropped.

2.4.5 SHOCK WAVES IN A LIQUID: THE PECULIAR FLUID

*The famous Florentine experiment, which so many Philosophical writers have mentioned as a proof of the incompressibility of water, will not, when carefully considered, appear sufficient for that purpose... But it was impossible for the gentlemen of the Academy del Cimento to determine, that the water which was forced into the pores and through the gold, was exactly equal to the diminution of the internal space by the pressure.*²⁴⁴

John CANTON
London 1761

*Shock waves in water differ greatly from those in air. If the pressure difference is the same, the shock velocity and the mass velocity are considerably less, and the temperature rise is enormously less. If the piston velocity (equals mass velocity) is the same in air and in water, then the shock velocity is considerably higher, the pressure difference very much higher and the temperature rise lower in the water case.*²⁴⁵

George B. KISTIAKOWSKY
Harvard University
Cambridge, MA 1941

Liquids occupy an interesting intermediate position between the gaseous and solid state, and were regarded for a long time as being incompressible matter {Florence Academy ⇒1660s}. Edmé MARIOTTE, the eminent French natural philosopher, asserted in his treatise *Mouvement des eaux et des autres corps fluides* ("Motion of Water and Other Fluidic Objects," published posthumously in 1686) that water is incompressible and hence has no elastic force. He also studied the

force of impact of water in the form of its speed of efflux through a small hole at the base of a reservoir. It took further 76 years until the English naturalist John CANTON {⇒1762} first demonstrated its – albeit very small – compressibility. In any liquid, the compressibility increases and the density decreases as the temperature rises. Therefore, unlike gases, the velocity of sound in liquids decreases (approximately linearly) as the temperature rises. However, water occupies a special position amongst liquids: the compressibility drops initially as the temperature rises to a minimum of about 60 °C, and only then does it increase. Therefore, initially the velocity of sound in water has a positive temperature coefficient and reaches a maximum value of 1,557 m/s at 74 °C. Above this temperature the velocity of sound in water decreases.

Real liquids, which have small but finite viscosities, differ widely in terms of their compressibility: in the low-pressure regime, in which the molecules are being pushed into effective contact, the viscosities of organic liquids increase under pressure at a rate that increases rapidly with increasing pressure; however, for water or monatomic mercury this rise in viscosity is comparatively small. At higher pressures, when the compressibility arises from a decrease in molecular volume, the volumes of ordinary liquids become surprisingly similar. Obviously, it is very difficult to model the complex behavior of liquids by defining a "perfect liquid" in analogy to the "perfect gas" that has played such an important role in the kinetic theory of gases. Eric D. CHISOLM²⁴⁶ and Duane C. WALLACE, two LANL scientists who recently proposed a theory for the dynamics of monatomic liquids, appropriately wrote, "Despite a long history of physical studies of the liquid state, no single theory of liquid dynamics has achieved the nearly universal acceptance of BOLTZMANN's theory of gases or BORN's theory of lattice dynamics of crystals. This shows the extraordinary theoretical challenge that liquids pose; they enjoy none of the properties that make either crystals or gases relatively tractable. A great deal of effort has been devoted to understanding liquids as hard-sphere systems, which do model the core repulsion present in real liquids, but omit the important potential energy effects..."

In shock wave physics, liquids and gases are often treated as *compressible fluids*. At pressures of 1 kbar or more, the densities of gases become of the same order of magnitude as those of their liquid phase, and there ceases to be any significant difference between the gas and the liquid. On the other hand, liquids and solids are also considered to be phases of *condensed matter*, and at sufficiently high pres-

²⁴⁴ J. CANTON: *Experiments to prove that water is not incompressible*. Phil. Trans. Roy. Soc. Lond. **52**, 640-643 (1761/1762).

²⁴⁵ See KISTIAKOWSKY ET AL. {⇒1941}.

²⁴⁶ E.D. CHISOLM and D.C. WALLACE: *Dynamics of monatomic liquids*. J. Phys. Condens. Matter **13**, R739-R769 (2001).

tures polymorphism phase transitions can occur. At first, the existence of dynamic polymorphism was never seriously considered by static high-pressure workers, since transformation rates observed in static experiments are classified as “sluggish,” ranging from minutes to days. However, the discovery of polymorphism in dynamic experiments demonstrated that

- ▶ the transformation rate between two polymorphs is large enough to be detectable in shock wave experiments; and
- ▶ the pressure at which transformation occurs dynamically agrees with an established static transition pressure.

“Shock wave splitting” provides clear evidence of first-order phase transitions, which are characterized by discontinuities in volume and entropy. In contrast, shock-induced second-order transitions involve phases for which volume and entropy are continuous, but higher derivatives of energy, specific heat, compressibility and thermal expansion are discontinuous {DUVALL & GRAHAM \Rightarrow 1977}. Second-order transitions may play an important role in shock-compressed solids such as ferromagnetic-to-paramagnetic iron alloys {CURRAN \Rightarrow 1961}, but second-order transitions and some effects that may be associated with them have not yet been studied in shock-compressed liquids.

Generally, a fluid is defined as a nonsolid state of matter in which the atoms or molecules are free to move past each other; *i.e.*, they offer no permanent resistance to change of shape. Liquids, most of which approach an ideal fluid in the sense that they cannot support shear stress, are much more difficult to compress than gases, since liquid molecules are already arranged such that they are close together. Liquids do not have unit cells; they are, to a first approximation, irregularly packed volumes of spheres; the arrangement of their atoms can be visualized as billiard balls jumbled in a bag. As a consequence, typical shock wave properties such as wave-steepening effects and supersonic propagation are clearly observable only at much higher shock pressures than for shock-compressed gases. Additionally, at the leading edge of the shock, dense fluids ($\rho > 1 \text{ g/cm}^3$) show thermodynamic characteristics that are markedly different from those of a viscous, heat-conducting gas, and above the viscous fluid limit they show a nonplastic solid response. For example, in the case of shock-compressed water, this limit is reached just below 13 kbar {WALLACE \Rightarrow 1982}.

There is also a remarkable difference if we compare gases with liquids in terms of their compressibility $\xi = \rho/\rho_0$: while gases can highly be compressed by static means up to $\xi > 1,000$, the maximum compression across a shock wave

in a gas cannot exceed a surprisingly small value which, for example for air ($\gamma = 1.4$) amounts to just six – a value which can easily be obtained by using a modern bicycle tire pump.²⁴⁷ On the other hand, liquids and solids can be shock-compressed to a higher degree than is possible with any static means presently available.

Depending on the pressure applied, a compressed liquid can solidify (or freeze), while a compressed solid can liquefy (or melt). Shock waves propagating in a gas-liquid mixture, such as in moist air, can generate shock-induced condensation effects, a phenomenon that caused much puzzlement in the pioneering era of supersonic wind tunnels {5th Volta Conf. \Rightarrow 1935}, and one that occurs when an aircraft is flying under particular conditions at supersonic speed: in this case it reveals itself as clouds partly that surround the fuselage or wings { \Rightarrow Fig. 4.14–F}.

Shock-compressed fluids in the liquid state, when compared to gaseous fluids, may show unusual properties (*e.g.*, high viscosity, low compressibility, phase transformations), and may generate complicated side effects (*e.g.*, cavitation). Since the density of a liquid is much higher than that of a gas – for instance, water is some 770 times more dense than air – hydrostatic buoyancy effects resulting from differences in hydrostatic pressure at different depths cannot be neglected. Compared to a gaseous environment, such effects occur in gases at much smaller dimensions, leading to typical phenomena such as upward movement, deformation and jet formation { \Rightarrow Fig. 4.16–E} of the gas bubble in an underwater explosion {BLOCHMANN \Rightarrow 1898; RAMSAUER \Rightarrow 1923; LAMB \Rightarrow 1923; KIRKWOOD & BETHE \Rightarrow 1942; COLE \Rightarrow 1948; UDEX Reports \Rightarrow 1950}.

Shock waves in liquids, particularly those in water, were barely studied until the beginning of World War II. However, a few remarkable contributions, described in more detail in the CHRONOLOGY, should be emphasized here.

Shock-Induced Freezing. Water – the most abundant liquid on Earth – is a highly unusual substance at atmospheric pressure, and so physicists expected it to be similar under high static and/or shock pressures.

The U.S. physicist Percy W. BRIDGMAN { \Rightarrow 1931}, who performed high-pressure studies on compressed liquids, demonstrated that water solidifies under static pressure in the

²⁴⁷ According to elementary shock theory, for an ideal gas, the *maximum compression ratio* at the shock front is given by $\xi = (\gamma + 1)/(\gamma - 1)$, where γ is the ratio of the specific heats at constant pressure and constant temperature, respectively. The limiting compression for a monatomic gas (*e.g.*, He, Ne, Ar, Kr, Xe, Rn) is $\xi = 4$, and for a diatomic gas (*e.g.*, H₂, O₂, N₂) it is $\xi = 6$.

pressure range 0–25 kbar, thereby producing seven different crystalline modifications of ice: *Ice I* to *Ice VII*, with *Ice II* being the most dense structure. During World War II, the German physicist and ballistician Hubert SCHARDIN {⇒1940/1941}, while studying ballistic phenomena in water and other liquids, was apparently the first to suggest *shock-induced freezing*. However, his ballistic impact experiments, in which he measured the temporal optical transparency of shock-compressed liquids, showed that water remains transparent behind the shock front. After World War II, with the advent of more advanced diagnostic techniques, this line of research was resumed both in the United States and the Soviet Union, but it gave ambiguous results. The Los Alamos scientists shocked water to 100 kbar, but found no sign of opacity due to freezing {WALSH & RICE ⇒1957}. Soviet researchers noticed a kink in the measured Hugoniot curve of water, from which they concluded that a shock-induced phase transition beginning at 115 kbar had occurred {AL'TSHULER ET AL. ⇒1958}. However, this result could not be confirmed by another Soviet group {ZEL'DOVICH ET AL. 1961, see AL'TSHULER ET AL. ⇒1958}. Very recently, this fascinating subject in shock physics was resumed in the United States: a multiple shock compression technique was used to prove that shock-compressed water does indeed freeze, even on a nanosecond time scale {DOLAN & GUPTA ⇒2004}.

Flash X-ray diffraction of shock-solidified liquids may provide valuable information on whether a new polycrystalline solid state has indeed been produced or whether this is a pseudo-effect (e.g., due to a shock-induced large increase of viscosity). However, initial experiments carried out in this area in the early 1970s by the author on shock-compressed CCl_4 {SCHAAFFS & TRENDLENBURG ⇒1948} using characteristic radiation (such as Mo-K α and Cu-K α from standard vacuum discharge flash X-ray tubes), were just too ambitious for their time and so they failed. The application of soft flash X-rays from laser-produced plasmas {WARK ET AL. ⇒1991} or further progress in the development of high-intensity pulsed soft X-ray lasers, combined with high-sensitivity MCP detectors {FARNSWORTH ⇒1930}, may enable shock researchers to follow the transition of a liquid from its amorphous state into a shock-induced polycrystalline or polycrystalline-like state in the future.

Corresponding static X-ray diffraction studies of the structures of liquids at high pressures and temperatures have been a long-standing goal in static high-pressure research. With the maturation of third-generation synchrotron sources, this goal was eventually attained a few years ago in Japan by

Yoshinori KATAYAMA²⁴⁸ and collaborators at the Japan Atomic Energy Research Institute, who observed a first-order liquid-liquid phase transition in phosphorus in a large-volume press. In addition to finding a known form of liquid phosphorus at low pressure – a molecular liquid comprising tetrahedral P_4 molecules – they found a high-pressure polymeric form at pressures above 1 GPa (10 kbar).

Liquefaction. The curious and unusual phenomenon of liquefaction can be achieved by starting from the gaseous as well as from the solid state: a *liquefaction shock wave* is a compression shock that converts vapor (i.e., a gas) into a liquid state. The existence of a liquefaction shock wave was first predicted on physical grounds and was later also proved experimentally {DETTLEFF ET AL. ⇒1979}. The liquefaction shock is a new phenomenon and one that is quite distinct from the well-known condensation of vapor in an expanding flow {5th Volta Conf. (PRANDTL) ⇒1935; HVA Peenemünde ⇒1939}.

On the other hand, the term *shock liquefaction* is used in solid-state shock wave physics to describe a first-order phase transition from the solid to the liquid state, also known as “shock melting” {KORMER ET AL. ⇒1965; ASAY ET AL. ⇒1976; DUVALL ET AL. ⇒1977}. Solids that are shock-compressed far beyond their yield stress can be treated as fluids to a first approximation.

Furthermore, the term *shock liquefaction* is also used in geology and seismology, but here it takes a quite different meaning: it designates a sudden, large decrease in the shearing resistance of a water-saturated cohesionless soil (such that as caused by seismic shocks or some other strain) which involves a temporary transformation of the material into a viscous fluid mass. Shock liquefaction is among the most catastrophic of all ground failures, and it has been observed to occur during almost all large earthquakes; it was extremely dramatic during the Kobe Earthquake {⇒1995} in Japan for example. The term *liquefaction* was apparently first used in a paper by A. HAZEN²⁴⁹ in which he described the failure of hydraulic fill sands in Calaveras Dam, located near San Francisco, CA: on March 24, 1918, the upstream toe of the under construction Calaveras dam suddenly flowed, the water gate tower collapsed and approximately 800,000 cubic yards (731,520 m³) of material moved around 300 ft (91.4 m). Apparently at the time of the failure none special disturbance was noticed.

²⁴⁸ Y. KATAYAMA, T. MIZUTANI, W. UTSUMI, O. SHIMOMURA, M. YAMAKATA, and K. FUNAKOSHI: *A first-order liquid-liquid phase transition in phosphorus*. *Nature* **403**, 170-173 (2000).

²⁴⁹ A. HAZEN: *Hydraulic-fill dams*. *ASCE Trans.* **83**, 1713-1745 (1920).

Water Hammer, Water Ram, Hydraulic Ram and Hydrodynamic Ram. These four terms relate to devices and/or effects that occur when a liquid mass is suddenly accelerated or decelerated, causing pressure pulses (weak shock waves) in the liquid.

The term *water hammer* or *water ram* originally referred to an instrument that has been used since at least the late 18th century to illustrate the fact that liquids and solids fall at the same rate in a vacuum. It consists of a hermetically sealed glass tube devoid of air and partially filled with water. When the tube is quickly reversed, the water falls to the other end with a sharp and loud noise like that of a hammer, thus impressively demonstrating that a liquid in a tube without air behaves as a compact mass. The instrument was made and sold by glass-blowers and barometer-makers.²⁵⁰ In the 19th century, this phenomenon was also known by the name *Kryophor* in Germany,²⁵¹ because it could be demonstrated with WOLLASTON's kryophor,²⁵² a curved glass tube provided with two spherical balloons at the end and partially filled with a liquid.

In hydraulics, the term *water hammer* [Germ. *Wasserschlag*, French *coup de béliet*] also describes the concussion or sound of water in a long pipe when its flow is suddenly stopped or when a live stream is suddenly admitted, such as by closing or opening a valve inserted in the line, respectively. This phenomenon, termed the *water hammer effect*, is detrimental in pipe systems, because the pressure pulse produced can propagate to remote areas and destroy tubes, valves, and other installations. This effect would most probably have been observed as far back as the time of the Roman Empire. For example, in Rome's highly impressive water supply system, which was constructed in the first century A.D., the water was brought overland in conduits and then fed into a vast network of small bronze, lead or ceramic pipes. Beginning in the 19th century, the problem of water hammer or hydraulic shocks in water supply lines became important in countries where large water supply systems had to be built to satisfy the rapidly increasing demands of urbanization, industry, and agriculture. The water hammer problem was first treated scientifically in Russia at the turn of the 19th century {KARELJIKICH & ZHUKOVSKY ⇨ 1898}.

Drops of liquid impacting onto a solid surface are also termed a *water hammer*. This water hammer effect can cause serious material damage it, and long proved to be a problem to steam turbine {⇨ Fig. 4.14–C} and high-speed naval propeller {Sir PARSONS ⇨ 1897; Brit. Committee of Invention & Research ⇨ 1915; S.S. COOK ⇨ 1928} designers and operators. In the 1960s, the same phenomenon became of increasing concern in the aerospace industry due to both serious rain erosion problems sustained by supersonic aircraft and missiles and anticipated blade erosion problems in the turbines of space-based power plants (for example, in megawatt or even gigawatt turbines earmarked for asteroid tug propulsion purposes), which would use liquid metals as the working fluid {HEYMANN ⇨ 1969}.

The term *hydraulic ram* originally referred to a device for pumping water. The French hot-air balloon pioneer Joseph-Michel MONTGOLFIER {⇨ 1796}, supported by the Swiss physicist Aimé ARGAND, successfully used the water hammer phenomenon to pump water {⇨ Fig. 4.2–M}. They called their pump a “hydraulic ram” [French *béliet hydraulique*]. In their water pump, the natural downward flow of running water was intermittently halted by a valve, so that the flow was forced upward through an open pipe into a reservoir.

The term *hydraulic ram* also designates an effect that can be generated by an object impacting and penetrating into a liquid – probably the oldest known shock wave effect in a liquid. The French natural philosopher Louis CARRÉ {⇨ 1705} observed a curious phenomenon where a bullet that is shot into a wooden box filled with water causes the box to blow up. The impacting bullet transfers a large amount of momentum to the water, generating a shock wave that ruptures the walls. In the 19th century, as the projectile velocities achieved by small firearms increased, a new type of injury from penetrating bullets was diagnosed: a high-velocity bullet not only cuts through tissues directly in its path but it also imparts sufficient kinetic energy to adjacent tissues to cause an explosion-like effect that results in injury to an area many times the diameter of the bullet. This dreaded phenomenon, based on the hydraulic ram effect, was first observed in the Prussian-French War (1870–1871), and both nations erroneously accused each other of having used explosive bullets, which were banned {St. Petersburg Declaration ⇨ 1868}.

²⁵⁰ J.A. SIMPSON and E.S.C. WEINER: *The Oxford English dictionary*. Clarendon Press, Oxford (1989), vol. 19, p. 996.

²⁵¹ *Meyers Konversations-Lexikon*. Bibl. Inst., Leipzig & Berlin (1897), vol. 15, p. 1003 “Sieden.”

²⁵² W.H. WOLLASTON: *On a method of freezing at a distance*. Phil. Trans. Roy. Soc. Lond. **103**, 71–74 (1813).

Ever since the first air battles were fought in World War I, the susceptibility of aircraft fuel tanks to ballistic impact has been a serious issue for military aircraft, whose fuel tanks cannot be fully armored against gun shots. When sufficiently energetic debris impact and penetrate a tank below the fuel level, the result of the energy transfer is an increase in pressure that can tear the tank apart. The subsequent fuel release can have catastrophic consequences. This hazard has also been termed a *hydraulic ram* {ANKENEY \Rightarrow 1977}.

In 1977, a Hydraulic Ram Seminar was held on this particular subject at the U.S. Air Force Flight Dynamics Laboratory (Wright-Patterson Air Force Base, OH).²⁵³ In the 1980s, empirical codes such as the Explicitly Restarted Arnoldi Method (ERAM) and the ABAQUS software for finite element analysis (FEA) were coupled to provide a complete hydraulic ram analysis: ERAM was used to determine hydrodynamic ram loads, and ABAQUS was used as a non-linear quasi-static analysis tool that took the peak pressures output from ERAM.

The study of hydraulic rams in commercial aviation was largely ignored until the Concorde disaster of July 25, 2000 in the commune of Gonesse after takeoff from Paris (113 casualties). This disaster resulted from the high-speed impact of an exploded tire fragment on a fuel tank on a wing, causing “hydraulic ram” shock waves to be set up in the fuel that led to tank rupture and then a catastrophic fire.²⁵⁴ Since then, such studies have received a lot of attention, particularly in Europe.

The term *hydraulic ram* is somewhat misleading, since it suggests a quasi-static compression phenomenon,²⁵⁵ whereas in reality the effect comprises at least four distinct sequential dynamic phenomena (or phases).²⁵⁶ Each of the four phases of a hydraulic ram contributes to structural damage and so they must all be accounted for in ballistic analysis.

- ▶ The *shock wave phase* occurs during the penetration of the tank by a projectile. Note that this occurs even though the projectile may be traveling at a subsonic speed with respect to the fuel tank.
- ▶ The *pressure field phase* (or *drag phase*) is characterized by relatively low pressures and long durations. Since the pressure field lies ahead of the projectile,

pressure field damage loads are greatest on the exit wall and lowest on the entrance wall.

- ▶ The *cavity collapse phase* occurs due to the fact that a high-velocity projectile imparts a large radial velocity to the fuel it displaces along its path.
- ▶ The *free surface phase* depends on the depth to which the tank is filled, and may occur either during or after the cavity collapse phase. The upward motion of the fuel reaching the top of the tank results in the generation of a large impulsive load on the top tank wall.

Instead of the term *hydraulic ram*, modern hydrodynamicists are increasingly tending to use the term *hydrodynamic ram* to denote the overall effect of the four phases listed above.

Underwater Explosions. Compared to gaseous explosions, underwater explosions encompass a wealth of complex and different phenomena. Their investigation is more challenging to the shock physicist and requires cameras with higher frame rates and shorter exposure times, because the velocities involved are higher (by a factor of almost five) than for explosions in air. In addition, proper illumination is more difficult to achieve because of the higher attenuation and greater scattering of light in water.

A distinctive feature of explosions in water is that the gas bubble pulsates between a series of maximum and minimum values for the bubble radius. In the early stages of the explosion, the bubble expands until the mean radius inside it falls below the pressure in the compressed water surrounding it. It then stops expanding and instead starts to contract. It contracts until its mean pressure exceeds that in the surrounding water, at which point it again expands outwards. During the contracting phase, compressive waves are sent inwards, giving rise to a converging spherical shock wave that is reflected at the center as an outgoing shock. A new shock wave is formed during each contraction, so multiple shocks are one characteristic of underwater explosions. However, beginning with the first contraction phase, the buoyancy effect distorts the spherical form of the bubble significantly, leading to a kidney-shaped bubble geometry and the generation of a vortex ring {COLE \Rightarrow 1948; SNAY \Rightarrow 1958; HOLT \Rightarrow 1977}. Novel effects observed for nuclear explosions generated underwater, at the surface or above it stimulated numerous investigations into their mechanisms and energy release {COLLINS & HOLT \Rightarrow 1968}.

²⁵³ S.J. BLESS and A.J. HOLTEN (eds.): *Hydraulic Ram Seminar*. Tech. Rept. AFFDL-TR-77-32. Wright-Patterson AFB, OH (May 1977).

²⁵⁴ J. MORROCCO and P. SPARACO: *Concorde team activates return-to-flight plan*. Aviation Week & Space Technology **154**, 38-40 (Jan. 22, 2001).

²⁵⁵ The large output piston (plunger) of a hydraulic press, an invention of the Englishman Joseph BRAMAH { \Rightarrow 1795}, is also called a “hydraulic ram.”

²⁵⁶ R.F. WILLIAMS: *Shock effects in fuel cells*. Final Rept. prepared for McDonnell-Douglas Corporation, Long Beach, CA. Poulter Laboratory, SRI, Menlo Park, CA (1969).

Shock wave effects in water resulting from underwater explosions were first observed in military applications. For example, Henry L. ABBOT {⇒1881} in the United States and Rudolf BLOCHMANN {⇒1898} in Germany studied underwater explosion phenomena associated with submarine mines, a subject that had become of increasing interest to all navies since the invention of the torpedo in the 1860s. During World War II, research on underwater explosions was driven forward on a large scale by the United States and England. Their UNDEX Reports {⇒1946}, published after the end of the war, include a wealth of data on underwater explosion phenomena and their analytical treatment, and even today are a rich source of information. Robert COLE's book *Underwater Explosions* {COLE ⇒1948}, which largely built on the results from research performed by the Allies during World War II, became a bestseller in this field, and is probably still the textbook consulted most often on the propagation and effects of shock waves in liquids.

Water Ricochets. Rebounding or “skipping” is a phenomenon that can easily be demonstrated by throwing flat stones along the surface of a pond at a low angle of elevation so as to make them rebound repeatedly from the surface of the water, raising a succession of jets – an action often called “playing ducks and drakes.” It was first studied scientifically by the Bohemian naturalist Marcus MARCI {⇒1639}. By observing their trajectory, he explained the rebound effect using the Law of Reflection {⇒Fig. 4.3–B}, which was already known in optics. *Ricochet firing*, which is also based upon rebound, was a French discovery made in 1697 by the military engineer Sébastien LE PRESTRE DE VAUBAN: a shot could be aimed so as to skip over the ground (or water) many times, which allowed areas protected from direct fire to be targeted. It also increased ballistic ranges considerably {DOUGLAS ⇒1851}. For example, test firings aboard HMS *Excellent*, used as a floating gunnery school at Portsmouth from 1859 onwards, revealed that at an elevation of one degree, the 800-yard (732-m) range of a 32-pound (14.5-kg) gun could be increased to 2,900 yards (2,652 m) after 15 grazes.²⁵⁷ Notes written at the time recommended that, “Ricochet firing requires a perfectly smooth sea. The closer the gun is placed to the water, the farther it ranges the shot. It might be advisable to heel the ship over by running in the opposite guns.”

This peculiar percussion phenomenon gained new interest with the advent of seaplanes and the need for them to land at high speed or on rough seas. Investigations performed in various countries, including the United States (KÁRMÁN & WATTENDORF 1929), Germany {WAGNER ⇒1932}, and the former Soviet Union (SEDOV & WLADIMIROW 1942), revealed that this skipping effect is a complicated combination of gliding and periodic bouncing which also generates finite-amplitude waves in the water. To extend the rough-water capabilities of seaplanes, important scientific progress was made in the theory of water impact and submerged lifting elements (hydrofoils). In the 1930s, the largest and fastest airplanes in the world were seaplanes, but after the outbreak of World War II their commercial and military significance diminished.

It is interesting to note here that “skipping” was also proposed in 1944 in Germany by the rocket engineer Eugen SÄNGER²⁵⁸ and by the mathematician Irene BREDT for long-range hypervelocity vehicles, where the vehicle would “bounce” along the denser air layers surrounding the Earth. Using such a “skip trajectory,” a combination of a ballistic trajectory with a glide trajectory, ballistic flight would go hand-in-hand with lifting flight.

Cavitation. Historically, Osborne REYNOLDS,²⁵⁹ a British engineer and physicist, was the first to observe cavitation phenomena in water flowing through a tube with a local constriction. He described these phenomena in a paper dated 1894. In accordance with the Bernoulli law, a region of lowered pressure is formed in the narrow part of the tube. If the flow rate is sufficiently great, the pressure falls to a value corresponding to the vapor pressure, which at room temperature is only about 20 mbar, causing the water to boil in the narrow cross-section of the tube. These empty *bubbles* (or *cavities*) carried along by the current collapse and vanish upon entering a region of increased pressure. The collapse of each bubble, which proceeds at a very high rate, is accompanied by a kind of a *hydraulic blow* that causes a sound (a click). The clicks from a large number of bubbles collapsing unite into one continuous sound, and this what is heard when water flows through a tube with a local constriction {KORNFELD & SUVOROV ⇒1944}.

²⁵⁸ E. SÄNGER and I. BREDT: *Über einen Raketenantrieb für Fernbomber*. Bericht U93538, Dt. Luftfahrtforsch. (1944). Engl. translation in: *A rocket drive for long-range bombers*. Rept. No. CGD-32, Tech. Info. Branch, Bureau of Aeronautics, Navy Dept., Washington, DC (1946).

²⁵⁹ O. REYNOLDS: *Experiments showing the boiling of water in an open tube at ordinary temperatures*. In: *Papers on mechanical and physical subjects*. Cambridge University Press, Cambridge (1901), vol. 2 (1881–1900), pp. 578–587.

²⁵⁷ *Early life and royal naval service. Muzzle-loading naval guns – some data*. Maritime history; <http://www.cronab.demon.co.uk/info.htm>.

Cavitation is understood as being the violent agitation of a liquid caused by the rapid formation and collapse of bubbles, transforming a liquid into a complex two-phase, liquid/vapor system. The term *cavitation* was coined in England {THORNYCROFT & BARNABY \Rightarrow 1895}. Cavitation became a subject of intense research in science and engineering shortly after the first use of steam turbines. In the 1880s, at the beginning of the age of steam turbines, erosion effects caused by cavitation were observed not only on the blade tips of turbine wheels but also on marine propellers that were initially driven at very high speeds in order to avoid losses involving high gear reduction between turbine and propeller. Studies of cavitation phenomena were prompted by both engineering requirements (to avoid cavitation erosion) {THORNYCROFT & BARNABY \Rightarrow 1895; S.S. COOK \Rightarrow 1928} and scientific curiosity {Lord RAYLEIGH \Rightarrow 1917; PRANDTL 1925; JOUGUET 1927; ACKERET 1938, LAUTERBORN ET AL. \Rightarrow 1972}. The central implosion of cavitation bubbles is accompanied by the emission of shock waves, which can have destructive effects. Russian researchers were the first suggest that the cavities can collapse asymmetrically and produce a liquid jet {KORN-FELD & SUVOROV \Rightarrow 1944}. John P. DEAR and John E. FIELD, two British physicists at Cavendish Laboratory, performed detailed investigations of this phenomenon: using high-speed photography they observed that asymmetric bubble collapse is indeed accompanied by jet formation, which they suggested as being the major mechanism for cavitation damage {DEAR & FIELD \Rightarrow 1988}. In addition, jet produced by the shock collapse of cavities might play a role in the ignition and propagation of explosive reactions {BOWDEN & MCONIE \Rightarrow 1965; COLEY & FIELD \Rightarrow 1970}.

Supercavitation. An extreme version of cavitation is *supercavitation*. In order to reduce the hydrodynamic drag of an object moving at high speed through a liquid (water), a single bubble is artificially formed that envelops the object almost completely. This technique has been pursued since the 1960s in naval warfare by both Soviet and western researchers. At velocities over about 50 m/s (180 km/h), blunt-nosed projectiles – so called “cavitators” – or prow-mounted gas-injection systems are used to produce these low-density gas pockets – so-called “supercavities.” With slender, axisymmetric bodies, such supercavities take the shape of elongated ellipsoids, ideally beginning at the forebody and trailing behind, with the length dependent on the speed of the body.²⁶⁰ Supercavitation

allows objects to achieve supersonic velocities in water {Naval Undersea Warfare Center \Rightarrow 1997; \Rightarrow Fig. 4.14-E}. However, it is apparently still difficult to maintain a complete artificial bubble over a longer period of time.

Photodisruptive Effect. Bubble collapse in a liquid and its associated shock pressure effects can now be generated over a very wide spatial/temporal range, covering meters/milliseconds down to nanometers/femtoseconds. An example of the upper limit of bubble dynamics is the gas sphere of an underwater explosion.²⁶¹ On the other hand, bubble dynamics at the lower limit encompass all microcavitation phenomena: for example, the irradiation of biological tissue with femtosecond laser pulses can result in ultrashort mechanical shock pulses causing a mini explosion – a phenomenon which has been termed the *photodisruptive effect*. It has been used in femtosecond laser nanosurgery to create a “nanoscalpel” capable of cutting nanometer-sized particles, such as chromosomes in a living cell {KÖNIG ET AL. \Rightarrow 1999}.

Cavitation is a very effective way of generating shock waves, and it is even used in the animal world. For perhaps millions of years, the species *Alpheus heterochaelis* of the family *Alpheidae* – the largest snapping shrimp to inhabit tropical and shallow seawaters, and one that reaches a body length of up to 55 mm – can clamp its claw so rapidly that a water jet is generated which causes a vapor bubble in the jet to swell and collapse with a distinct “snap.” Recent studies performed at the University of Twente by the Dutch scientist Michael VERSLUIS and German collaborators at the Universities of Munich and Marburg revealed that the very short shock pulse emitted has a peak pressure of about 80 bar measured with a needle hydrophone at a distance of 4 cm from the claw {LOHSE ET AL. \Rightarrow 2000; \Rightarrow Fig. 4.1-Z}. The shock wave is apparently used to stun or kill small prey. In Germany, the snapping shrimp is appropriately called “pistol shrimp” [Germ. *Pistolenkrebs*].²⁶²

Sonoluminescence. The conversion of acoustical or shock wave energy into optical energy is a mysterious phenomenon. The light emission produced in this way from gaseous bubbles in liquids is termed *sonoluminescence*. In the early 1930s, it was discovered in France that a photographic plate

²⁶¹ In an underwater explosion the maximum bubble radius R_{\max} is given by $R_{\max} = J(W/Z)^{1/3}$, where W = charge weight in lb, Z = total hydrostatic head (including that of the atmosphere) in ft, J = radius constant (= 12.6 for TNT). For instance, the maximum bubble radius of a 300-lb charge of TNT which explodes in 30-ft depth is about 21 ft; {SNAY \Rightarrow 1958}, p. 267.

²⁶² R. ALTEVOGT: *Höhere Krebse*. In: (B. GRZIMEK, ed.) *Grzimeks Tierleben. Enzyklopädie des Tierreiches*. Kindler-Verlag, Zürich, vol. I (1971), p. 487.

²⁶⁰ S. ASHLEY: *Warp drive underwater*. *Scient. Am.* **284**, 62-71 (May 2001).

could be fogged in the presence of a cavitation field generated by ultrasound in water.²⁶³ It had previously been assumed that this effect arose from the nucleation, growth and collapse of gas-filled bubbles in a liquid. Sonoluminescence produced from single bubbles allowed much better insights into this effect and its characteristics.²⁶⁴ However, theories on the origin of sonoluminescence are still somewhat controversial.²⁶⁵ The most plausible explanation for the origin of the extremely short bursts of light emitted from the bubble is that an imploding shock wave is generated within the bubble during the final stages of collapse which heats up gas inside the bubble and generates light. Experimental results obtained by three groups at American Universities (Yale, WA and Los Angeles, CA) support this explanation for sonoluminescence – namely that a collapsing bubble creates an imploding shock wave. These three groups all recorded sharp acoustical pops during the sonoluminescence process.²⁶⁶

Very recently, it was observed that the snapping shrimp also creates a flash of light during shock wave emission, which the discoverers have appropriately called “shrimpluminescence” {LOHSE ET AL. 2000}.

Electrohydraulic Effect. First observed in England {SINGER & CROSSE \Rightarrow 1815} and later rediscovered in the United States {RIEBER (1947), \Rightarrow 1951} and the former Soviet Union {JUTKIN \Rightarrow 1950}, the *electrohydraulic effect* uses a powerful high-voltage discharge to generate strong shock waves, with the resulting strong current pulse being fed into either a thin metallic wire submersed in water or a spark gap submersed in an electrically nonconducting (organic) liquid. This effect was first highlighted by the Latvian urologist Viktor GOLDBERG { \Rightarrow 1959}, who first successfully applied it to the disintegration of bladder stones in man. His method has been called “electrohydraulic shock lithotripsy.” Later, this effect was also used for the disintegration of rocks, in well-drilling, and for grinding materials. Applications in production technology also include high-speed deformation of metals and intensification of processes in chemical and chemical-metallurgical engineering.

2.4.6 SOLID-STATE SHOCK WAVE PHYSICS: INITIATION BY NUCLEAR WEAPONEERS

*Shock wave physics as we know it today owes its genesis and entire formation period to a minor industrial revolution of precision casting, pressing and machining of explosives. This revolution and in addition the long-term support for equation-of-state research were entirely the result of the World War II crash program to develop a nuclear weapon.*²⁶⁷

John W. TAYLOR
Los Alamos National Laboratory
Los Alamos, NM 1983

*In early 1948, the scientific leadership of the All-Union Research Institute of Experimental Physics (VNIIEF) set experimenters a fundamental task of determining the equations of state and the shock compressibility of fissioning materials at megabar pressures. Because of the lack of accurate equations of state, it was impossible to predict unambiguously the power of the first A-bomb variant then in preparation for a test, nor could alternative bomb models be readily compared and assessed.*²⁶⁸

Lev V. AL'TSHULER
Institute of High Temperatures
Moscow 1996

In solid amorphous or noncrystalline materials, the component atoms or molecules are usually held together by strong forces, which therefore occupy definite positions relative to one another. In crystalline solids, however, the atoms (and molecules) are not only held in place, they are also arranged in a definite order that is constantly repeated throughout the sample; this periodic arrangement of atoms in a crystal is termed a *lattice*. In a crystal, an atom never strays far from a single, fixed position; the thermal vibrations associated with the atom are centered about this position. Shock propagation through such a lattice diminishes the *unit cell* that is representative of the entire lattice. Obviously, shock wave propagation through solids is far more complex than through a gas.

The Rankine-Hugoniot relationships {RANKINE \Rightarrow 1869; HUGONIOT \Rightarrow 1887}, which relate the thermodynamic state of the medium behind the shock front to its initial state, the shock wave velocity and the particle velocity, also proved most useful in the further evolution of solid-state shock wave physics: detailed experimental investigations of shock waves and the

²⁶³ N. MARINESCO and J.J. TRILLAT: *Actions des ultrasons sur les plaques photographiques*. C. R. Acad. Sci. Paris **196**, 858-860 (1933).

²⁶⁴ D.F. GAITAN: *An experimental investigation of acoustic cavitation in gaseous liquids*. Ph.D. thesis, University of Mississippi (1990).

²⁶⁵ C.M. SEHGAL: *Sonoluminescence*. In: (G.L. TRIGG, ed.) *Encyclopedia of applied physics*. VCH, New York etc., vol. 19 (1997), pp. 1-23.

²⁶⁶ *Sonoluminescence research vibrates with activity*. AIP Bulletin of Physics News No. 299 (Dec. 13, 1996).

²⁶⁷ J.W. TAYLOR: *Thunder in the mountains*. In: (J.R. ASAY, R.A. GRAHAM, and G.K. STRAUB, eds.) *Proc. 3rd Conference on Shock Waves in Condensed Matter* [Santa Fe, NM, July 1983]. North-Holland, Amsterdam etc. (1984), pp. 3-15.

²⁶⁸ L.V. AL'TSHULER: *Experiment in the Soviet atomic project*. In: (I.M. DREMIN and A.M. SEMIKHATOV, eds.) *Proc. 2nd Int. A.D. Sakharov Conference on Physics* [Moscow, USSR, May 1996]. World Scientific, Singapore (1997), pp. 649-655.

shock-induced properties of materials have essentially been made possible by devising ways to measure some of these parameters, from which the others could be derived by the Rankine-Hugoniot relationships. Initially, however, experimentalists lacked the diagnostic means to temporally resolve the shock wave parameters, and for many years progress in understanding shock waves in solids was closely dependent on progress in fast electronics and high-speed photography.

The most important (largely theoretical) works on shock waves in condensed matter dating from the period 1808–1949 have been brought together into a single collection.²⁶⁹ Important papers from 1948 to the present were later added to this original collection, allowing research workers and historians to trace the major developments leading to the establishment of the unique field of shock compression in solids.²⁷⁰

Roots. Historically, *solid-state shock wave physics* is an outgrowth of classical percussion, which was established in the 17th century, but the main push into this new area of research came from 19th century pioneers of classical shock wave theory, who did not limit their analyses to fluids, but also reflected on the peculiarities of shock waves in solids. In his famous treatise *On the Thermodynamic Theory of Waves of Finite Longitudinal Disturbance*, the Scottish civil engineer William J.M. RANKINE {⇒1869} clearly states that his derived relations are valid “for any substance, gaseous, liquid or solid.” Subsequent works on this subject addressed the shock-compressed solid state in more detail {CHRISTOFFEL ⇒1877; HUGONIOT ⇒1889; DUHEM ⇒1903; HADAMARD ⇒1903; JOUGUET ⇒1920}. In addition, important contributions from theoretical physicists also stimulated the evolution of shock wave physics in solids. Prominent examples include:

- ▶ various laws and theories of elastic percussion {HUYGENS ⇒1668/1669; EULER ⇒1737; D. BERNOULLI ⇒1770; HODGKINSON ⇒1833; Lord KELVIN ⇒1879; HERTZ ⇒1882};
- ▶ the first theory of elasticity {MAXWELL ⇒1850};
- ▶ the equation of state for solid matter based on lattice vibration theory, developed by the German physicists Gustav MIE (1903) and Eduard GRÜNEISEN {1912 & ⇒1926}; and
- ▶ theories on the dynamic plasticity of metals proposed by Geoffrey I. TAYLOR (1942), Theodore VON KÁRMÁN (1942) and Khalil A. RAKHMATULIN (1945) {B. HOPKINSON ⇒1905}.

In contrast to the rapid and steady progress made in shock wave physics in gaseous matter since the 1870s, research on shock-compressed solids evolved only very slowly. The main reason for this was certainly the need for high-speed diagnostics with submicrosecond resolution, which were not – with just a few exceptions – available until after World War II, and were even then initially confined to only a few laboratories.²⁷¹ Early researchers studying the dynamic properties of solids, particularly those interested in their rate-dependent strength, had to rely on simple experimental techniques. For example, the British engineer John HOPKINSON {⇒1872} measured the strength of a steel wire when the wire was suddenly stretched by a falling weight. He made the important observation that the strength is much greater under rapid loading than in the static case, a puzzling phenomenon that was later investigated in more detail by his son Bertram HOPKINSON {⇒1905}, who occupied the chair of applied mechanics at the University of Cambridge. He also discovered *spallation*, a curious fragmentation phenomenon that occurs at the back side of a metal plate loaded on its front side by a high explosive {B. HOPKINSON ⇒1912}, or by the hypervelocity impact of a solid body {⇒Fig. 4.3–U}. HOPKINSON’s results sowed the seeds of modern materials dynamics, a field that has grown steadily ever since, and which has become an indispensable tool in the computer modeling of structural behavior under high loading rates.

In the 19th century, the British engineer Charles A. PARSONS {⇒1892}, inventor of the multistage steam turbine, and the French chemist Henri MOISSAN, a professor at the University of Paris, attempted to use shock waves to induce polymorphism in solids (particularly in carbon to produce artificial diamonds).²⁷² However, their efforts did not provide any clear evidence, and were just too ambitious for their time. An important step toward this goal was the later work on the effects of static high pressure on a large number of liquid and solid substances carried out by the U.S. experimental physicist Percy W. BRIDGMAN at Harvard College, Cambridge, MA. Throughout a long-lasting campaign (1903–1961), BRIDGMAN laid the foundations for understanding the behav-

²⁶⁹ J.N. JOHNSON and R. CHÉRET (eds.): *Classic papers in shock compression science*. Springer, New York (1998).

²⁷⁰ J.N. JOHNSON and R. CHÉRET: *Shock waves in solids: an evolutionary perspective*. Shock Waves 9, No. 3, 193–200 (1999).

²⁷¹ At this point, the diagnostic instruments with the highest time resolution were mechanically driven streak cameras, which provided records of distance as function of time. At the end of World War II, the fastest camera available was the U.S. Bowen RC-3 rotating mirror camera, which had a writing speed of 3.1 mm/μs – i.e., 1 mm on the film plane corresponded to a time span of about 320 ns.

²⁷² A medium undergoing shock-induced polymorphism – i.e., a first-order phase transition ($\Delta V < 0$) – exhibits discontinuities in slope of the Hugoniot curve at the boundaries of the mixed phase region. • In solid matter, the Hugoniot curve can also show a discontinuity (known as a “cusp”), where elastic failure occurs.

ior of matter under static high pressures, which earned him the 1946 Nobel Prize for Physics.

In this early era, when even static high-pressure research was still in its infancy and had to battle against many technical problems with achieving such high pressures, shock waves generated by high explosives were already considered to be an easy way of reaching high pressures, although appropriate high-speed instrumentation for detecting and recording physical parameters of interest was not yet available. Compared to static methods, the use of detonation to achieve very high pressures is indeed surprisingly simple, particularly when using Mach reflection of cylindrically convergent shock waves. For example, the U.S. physicists George R. FOWLES and William M. ISBELL at SRI's Poulter Laboratory devised a coaxial set-up comprising a hollow cylinder of high explosive that generated shock pressures of up to 1.9 Mbar in the center of an enclosed test sample – a cylindrical copper rod in their experiment. Their device was only about the size of a Coca-Cola bottle {FOWLES & ISBELL \Rightarrow 1965; \Rightarrow Fig. 4.13–L}.

Establishment and Motivations. Contrary to the foundations of gas dynamics, which were mainly built upon European contributions, the foundations of modern solid-state shock wave physics were laid mainly in the United States and the former Soviet Union. Initiated during World War II, such investigations were exclusively motivated by military requirements.

On the one hand, research in the United States followed classical paths aimed at better understanding the dynamic responses of materials, particularly those of metals, under rapid loading conditions such as the penetration of a high-speed projectile into armor or its attack by high explosives, as well as appropriate protection measures – *i.e.*, research was carried out mostly according to the classic “terminal ballistics cycle” (*see* Sect. 2.3.3). During the war, U.S. activities in this subject of vital interest were coordinated by the National Defense Research Committee (NDRC), and the results were summarized in a confidential report²⁷³ distributed in 1946, which covered the topics of terminal ballistics, dynamic properties of matter, and protection. On the other hand, solid-state shock wave physics was an outgrowth of nuclear weapons research related to the Manhattan Project { \Rightarrow 1942}. The results from these secret studies were initially classified for years.

A historic review of this new branch of dynamic high-pressure physics was apparently first published in 1983 by the

physicist John W. TAYLOR,²⁷⁴ a former participant of the Manhattan Project. He remembered the beginning of shock wave physics at Los Alamos, “The history begins with a few hastily constructed demonstration experiments and ends with a new field of scientific inquiry.” Another historic review was given in 1991 by the U.S. solid-state physicist Charles E. MORRIS,²⁷⁵ which emphasized the pioneering shock wave research and equation-of-state studies at Los Alamos in the 1950s.

The first paper on the experimental study of shock wave propagation in solids, which was entitled *The Propagation of Shock Waves in Steel and Lead* and published in a British journal, was written by Donald C. PACK and coworkers {PACK ET AL. \Rightarrow 1948}, three physicists at the Armament Research Department (ARD) of the British Ministry of Supply. They investigated the stress system set up by an explosive detonating in contact with a metal surface, then the most basic and commonly used arrangement for generating high-pressure shock waves in any solid specimen.

The first review article on the progress of shock wave research in solids was not given until 1955: the U.S. physicist Roy W. GORANSON, who in 1945 initiated a program at Los Alamos Scientific Laboratory to systematically study the equations of state of various materials, presented the first data on the dynamic compressibility of metals. This allowed the first quantitative comparisons with BRIDGMAN's static measurements {GORANSON ET AL. \Rightarrow 1945 & 1955}. The classic, most widely cited, work in this new field of science was published in 1958 by three Los Alamos scientists {RICE, WALSH & MCQUEEN \Rightarrow 1958}. Their pioneering paper *Compression of Solids by Strong Shock Waves*, a landmark in the evolution of solid-state shock wave physics, was later appropriately commented on by the Sandia shock scientist Robert GRAHAM { \Rightarrow 1993}, “Almost overnight, ordnance laboratories throughout the world were able to convert technology developed for weapons into technology for visionary studies of matter in a new regime. Swords forged for nuclear weapon development were beaten into high pressure science plowshares.” Since then, an ever-increasing number of investigations have led to a considerable improvement in methods of generating dynamic pressures and their diagnostics as well as to refinements of numerical thermodynamic models.

One of the main goals for postwar solid-state shock wave research was the development of the hydrogen bomb – a complex and difficult task that required basic knowledge of how solid matter behaves under ultrahigh dynamic pressures that was previously not available. Progress in solid-state

²⁷³ E.P. WHITE (ed.): *Effects of impact and explosions*. Summery Tech. Rept. AD 221 586, Div. 2 of NDRC, Washington, DC (1946).

²⁷⁴ See reference given in footnote 267.

²⁷⁵ C.E. MORRIS: *Shock-wave equation-of-state studies at Los Alamos*. Shock Waves 1, 213–222 (1991).

shock wave physics is rather well documented in the open literature. In the Western World, the stepwise progress made and developmental highlights have been reviewed over the years in numerous articles contributed by researchers working at the forefront of this field, such as by

- ▶ Melvin H. RICE and associates { \Rightarrow 1958} at Los Alamos Scientific Laboratory (LASL), New Mexico;
- ▶ George E. DUVALL²⁷⁶ and George R. FOWLES, and William J. MURRI and associates { \Rightarrow 1974} at Poulter Laboratory of SRI, Menlo Park, CA;
- ▶ Sefton D. HAMANN { \Rightarrow 1966} at the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Melbourne, Australia;
- ▶ Robert A. GRAHAM²⁷⁷ and Lee DAVISON at Sandia Laboratories in Albuquerque, New Mexico;
- ▶ Budh K. GODWAL²⁷⁸ and associates at Bhabha Atomic Research in Bombay, India; and
- ▶ George DUVALL²⁷⁹ and Yogendra M. GUPTA²⁸⁰ at the Shock Dynamics Laboratory of Washington State University in Pullman, Washington.

Independent of nuclear weapons research performed in the framework of the Manhattan Project, similar work was also initiated in the former Soviet Union's Nuclear Center located in Arzamas-16 [now Sarov]. This institution [now the Russian Federal Nuclear Center of the All-Russian Scientific Research Institute of Experimental Physics (RFNC-VNIIEF)], then headed by Academician Yulii B. KHARITON, was, from its very conception up to 1996, in many senses a "hidden world," where a multi-disciplinary team of physicists, mathematicians, designers and high-speed instrumentation engineers was provided with highly favorable working conditions, and where fundamental science and defense mutually benefited from one another.²⁸¹ Motivation and development of solid-state shock wave physics went along similar lines. A considerable number of eminent physicists, in par-

ticular Yakov B. ZEL'DOVICH and Lev V. AL'TSHULER, significantly contributed to the fields of detonation physics and dynamic high-pressure physics.²⁸² The first Soviet results on dynamic equations of state for a number of metals were not published in the open literature until 1958.²⁸³ In 1965, AL'TSHULER,²⁸⁴ the patriarch of Russian solid-state shock wave physics, reviewed the use of shock waves in high-pressure physics, and, more recently, the development of dynamic high-pressure techniques in the former Soviet Union, some of which were more advanced than those developed in the Western World.²⁸⁵

Beginning in the early 1950s, dynamic high-pressure physics was also increasingly applied beyond military circles, thereby pushing the upper limit of achievable pressures far beyond the static pressures achievable at that time. Dr. Thomas POULTER,²⁸⁶ the first director of the Poulter Laboratory in Menlo Park, CA, remembered anecdotally, "We found that with the instrumentation available to us in the Poulter Laboratory we could conduct most of the experiments that I had done earlier with static pressures, but all of which were under one million psi [about 68 kbar]. After attending the Gordon Conference on High Pressure Physics [at Kimball Union Academy in Meriden, NH] where pressures were plotted up to 3 feet high and on a 3' \times 4' chart and pressures obtained and studied by P.W. BRIDGMAN (who had probably done more high pressure work than all of us combined) were on a 3" \times 4" lower left corner of the same chart, he [BRIDGMAN] commented, 'one hates to spend a lifetime in a field and see it pushed into such a small corner as that.'"

In particular, ambitious static high-pressure researchers targeted the "magic" limit of about 3.65 Mbar, a value considered by geophysicists to be the gravitationally generated pressure at the center of the Earth. Modern static compression techniques have even surpassed this limit. In 1990, Arthur L. RUOFF,²⁸⁷ a professor of materials science at Cornell University, and his collaborators produced static pressures of

²⁷⁶ G.E. DUVALL and G.R. FOWLES: *Shock waves*. In: (R.S. BRADLEY, ed.) *High-pressure physics and chemistry*. Academic Press, New York, vol. 2 (1963), pp. 209-291.

²⁷⁷ R.A. GRAHAM and L. DAVISON: *Shock compression of solids*. Phys. Repts. **55**, 255-379 (1979).

²⁷⁸ B.K. GODWAL, S.K. SIKKA, and R. CHIDAMBARAM: *Equation of state theories of condensed matter up to about 10 TPa*. Phys. Repts. **102**, 121-197 (1983).

²⁷⁹ G.E. DUVALL: *Shock wave research: yesterday, today and tomorrow*. In: (Y.M. GUPTA, ed.) *Proc. 4th APS Topical Conference on Shock Waves in Condensed Matter* [Spokane, WA, July 1985]. Plenum Press, New York (1986), pp. 1-12.

²⁸⁰ Y.M. GUPTA: *Shock waves in condensed materials*. In: (S.P. PARKER, ed.) *The encyclopedia of science and technology*. McGraw-Hill, New York, vol. 16 (1987), pp. 382-386.

²⁸¹ V.A. TSUKERMAN and Z.M. AZARKH: *Arzamas-16: Soviet scientists in the nuclear age: a memoir*. Bramcote, Nottingham (1999).

²⁸² Y. KHARITON, K. ADAMSKII, and Y. SMIRNOV: *The way it was*. Bull. Atom. Sci. **52**, No. 6, 53-59 (1996).

²⁸³ L.V. AL'TSHULER ET AL.: *Dynamic compressibility and equation of state of iron under high pressure*. Sov. Phys. JETP **7**, 606-614 (1958); *Dynamic compressibility of metals under pressures from 400,000 to 4,000,000 atmospheres*. Ibid. **7**, 614-619 (1958).

²⁸⁴ L.V. AL'TSHULER: *Use of shock waves in high pressure physics*. Sov. Phys. Uspekhi **8**, 52-91 (1965).

²⁸⁵ L.V. AL'TSHULER ET AL.: *Development of dynamic high-pressure techniques in Russia*. Physics Uspekhi **42**, 261-280 (1999).

²⁸⁶ T.C. POULTER: *Over the years*. Library of Stanford Research International (SRI), Menlo Park, CA (1978), p. 94.

²⁸⁷ A.L. RUOFF, H. XIA, H. LUO, and Y.K. VOHRA: *Miniaturization techniques for obtaining static pressures comparable to the pressure at the center of the Earth: X-ray diffraction at 416 GPa*. Rev. Scient. Instrum. **61**, 3830-3833 (1990).

up to 4.16 Mbar in the laboratory via special diamond-anvil cells. Two years later they pushed this limit even further, up to 5.6 Mbar.²⁸⁸

BRIDGMAN's results {⇒1911, 1925 & 1931} gave modern shock physicists their first clues about the static compressibility of solids at high pressures and the stress-dependent plasticity of metals, thus arousing their curiosity about how substances would behave under dynamic pressures. This also promoted various other spectacular investigations, *e.g.*, on shock-induced polymorphic transitions in iron {BANCROFT ET AL. ⇒1956}, on possible ice modifications of shock-compressed water {SCHARDIN 1940/1941; RICE & WALSH ⇒1957; AL'TSHULER ET AL. ⇒1958}, on shock-induced transformations of quartz into high-pressure polymorphs {CHAO ET AL. ⇒1960; SHOEMAKER & CHAO ⇒1961}, and of shocked graphite into diamond {DECARLI & JAMIESON ⇒1961}. Today dynamic and static high-pressure methods of generation, calibration and measurement do not compete with one another, but are used instead to complement each other, as shown for the example of the extension of the "ruby scale" {BARNETT ET AL. ⇒1973}.²⁸⁹

Materials Dynamics. Modern testing methods for studying the responses of materials under shock loading conditions are closely related to percussion. The *Charpy test* {CHARPY ⇒1901} and the *Izod test* {IZOD ⇒1905}, two fracture toughness tests used at relatively low strain rates ($c.10^1$ – 10^2 s⁻¹), use the impact energy of a single blow of a swinging pendulum. The energy absorbed, as determined by the subsequent rise in the pendulum, is a measure of the impact strength or notch toughness.

To a large extent, many high-rate testing methods are based on the planar impact of two bars, a basic 1-D arrangement which had already been treated by numerous researchers, both theoretically {EULER ⇒1737 & 1745; W. RICHARDSON 1769, *see* GALILEI ⇒1638; POISSON ⇒1811; CAUCHY ⇒1826; F.E. NEUMANN 1857/1858, *see* NEUMANN ⇒1885; DE SAINT-VENANT ⇒1867} and experimentally {RAMSAUER ⇒1909; DONNELL ⇒1930}. Today numerical analyses of 2-D and 3-D impact phenomena, ranging from stiff to flexible structures and also including vibration and wave effects, are of great practical concern in engineering {STRONGE ⇒2000}.

Today a variety of planar impact tests are widely used in high-rate materials testing; prominent examples include

- ▶ the *Hopkinson pressure bar* {B. HOPKINSON ⇒1914}, which was further developed into the *split Hopkinson pressure bar* or *Kolsky bar* {KOLSKY ⇒1949};
- ▶ the *Taylor test* {G.I. TAYLOR & WHIFFIN ⇒1948};
- ▶ the *flyer-plate method* {MCQUEEN & MARSH ⇒1960}; and
- ▶ the *planar impact test* using a high-velocity projectile {HUGHES & GOURLEY 1961, *see* CROZIER & HUME ⇒1946}.

Modern methods of performing high-rate materials testing are based on the generation and careful diagnostics of uniaxial shock waves in the test specimen as well as on analyses supported by complex numerical modeling on a microscopic level, thereby averaging micro-processes over a "relevant volume element" in a so-called "mesomodel" which contains a statistical number of micro-units in order to get a continuum model {CURRAN ET AL. ⇒1987}.²⁹⁰ The response of materials to high-velocity impact loading, which is governed by both thermomechanical and physical processes, spans a wide region of material behavior, ranging from high impact pressures and temperatures where thermodynamic effects prevail, to low pressures where mechanical properties are important.²⁹¹

Dynamic Fracture. *Fracture mechanics* is a branch of solid mechanics that is concerned almost entirely with fracture-dominant failure and deals with the behavior of cracked bodies subjected to static and/or dynamic stresses and strains. While such research was stimulated during the Industrial Revolution by the many accidents resulting from the failure of mechanical structures (such as steam-boilers, railway equipment, *etc.*), fracture mechanics as a science originated in the 1920s from a study of crack propagation in brittle materials, predominantly in glass.²⁹² *Fracturing* is a natural dynamic process in which material bonds are broken and voids are created in a previously intact material.

²⁸⁸ A. L. RUOFF, H. XIA, and Q. XIA: *The effect of a tapered aperture on X-ray diffraction from a sample with a pressure gradient: studies on three samples with a maximum pressure of 560 GPa*. *Rev. Scient. Instrum.* **63**, 4342-4348 (1992).

²⁸⁹ W.B. DANIELS: *High-pressure techniques*. In: (G.L. TRIGG, ed.) *Encyclopedia of applied physics*. VCH, New York *etc.*, vol. 7 (1993), pp. 495-509.

²⁹⁰ The word *mesomodel* is a contraction of *meso-scale model* (meso means "medium"). Mesomodels are used, for example, for numerical simulations of the multiphase behavior of materials under dynamic load, and for the localization of and damage computation in laminates. A *laminar* is considered, at the mesoscopic scale, to be a stack of homogenized plies and interfaces.

²⁹¹ J.R. ASAY and G.I. KERLEY: *The response of materials to dynamic loading*. *Int. J. Impact Engng.* **5**, 69-99 (1987).

²⁹² A historical review of fracture mechanics was given by M. JANSSEN, J. ZUIDEMA, and R.J.H. WANHILL in their book *Fracture mechanics*. Dup Blue Print, Delft (2002) & Spon Press, London (2004), chap. 1.

The most striking fracture phenomena are the initiation, propagation and branching of cracks, which were first investigated in transparent brittle materials such as glass and Plexiglas using high-speed cinematography {SCHARDIN \Rightarrow 1954}. These studies showed that cracks propagate slower than the longitudinal speed but faster than the shear wave speed in the material. Based upon predictions from classic continuum mechanics, it was widely believed that a brittle crack could not propagate faster than the longitudinal wave speed. However, later studies performed at high energy rates using a ruby laser showed that cracks can also propagate along weak crystallographic planes supersonically in regard to the longitudinal wave speed {WINKLER ET AL. \Rightarrow 1970}. More recent studies in brittle polyester resin have shown that, when cracks propagate faster than the shear wave speed, a traveling Mach cone is created which consists of two shear shock waves. Apparently, these results have similarities to shallow earthquake events {ROSAKIS ET AL. \Rightarrow 1999}.

The term *dynamic fracture* denotes the effects of inertia resulting from the rapid propagation of a crack, and the label “dynamic loading” is attached to the effects of inertia on fracture resulting from rapidly applied loads.²⁹³ In the past, various mathematical attempts were made to understand dynamic fracture: both the threshold conditions that trigger this process, and the kinetics by which it proceeds. A landmark in the evolution of modern fracture mechanics was the development of mesomechanical²⁹⁴ failure models by the U.S. metallurgist Troy W. BARBEE²⁹⁵ and coworkers. They realized that the nucleation, growth, and coalescence of microscopic voids, cracks, or shear bands in the failing material could be treated as the development of a new phase, and that quantitative post test analysis of recovered specimens could be used to develop nucleation and growth functions for the process. This era of dynamic fracture research was documented in a 1987 review paper {CURRAN ET AL. \Rightarrow 1987}. The latest development in this field are atomistic models for simulating materials failure that involve up to one billion atoms and the use of supercomputers; this area of research is known as “molecular dynamics” {ABRAHAM & GAO \Rightarrow 2000}. Such simulation studies have demonstrated that the

limiting speed of fracture is the longitudinal wave speed in harmonic (linear) solids. Also, in anharmonic solids the crack velocity can even exceed the longitudinal wave speed, thus becoming truly supersonic.

Equations of State. The large number of investigations on shock waves and their physical effects that have been carried out so far in solids have revealed that solids exhibit rather complex behavior in comparison to gases and liquids. Most solids exhibit an elastic-plastic behavior – *i.e.*, they will obey the Law of Linear Elasticity {HOOKE \Rightarrow 1679} until a yield condition is reached above which the solid will deform plastically. For stresses much higher than the so-called “yield stress,” a solid behaves like a fluid to a first approximation, since the percentage deviations from the isotropic stress distribution are small. Therefore, in order to describe the shock compression of a solid material in terms of an equation of state, a form similar to the equation of state for a gas or a liquid was assumed.

In the early period of shock wave research, the simple *Murnaghan equation* {MURNAGHAN \Rightarrow 1937} was proposed, which is similar to the *Tait equation* {TAIT \Rightarrow 1888} for shock-compressed liquids. However, neither of these equations consider any shock heating. One major advance was the application of the *Mie-Grüneisen equation* {GRÜNEISEN \Rightarrow 1926} to shock-compressed solids {WALSH, RICE, MCQUEEN & YARGER \Rightarrow 1957}, which became probably the most commonly used equation of state in solid-state shock wave physics. However, theories describing the thermodynamic state under shock loading – which therefore also take into account rate-dependent and structural properties such as porosity and viscosity – have proved to be very complex and are still in development. In addition, the shock characterization and thermodynamic behavior of composite materials, which have been increasingly used since the 1970s in military and space applications to provide effective shields against high-velocity impact {WHIPPLE \Rightarrow 1947}, are a particular challenge to theoreticians.

The shock-compressed state of liquids and solids is not usually described and characterized by its “rapidity,” as in gas dynamics (with the Mach number), but rather by the shock pressure – an historic relic of static high-pressure research which, as it steadily pushed the pressure limit higher and higher, used to announce its progress in terms of the maximum hydrostatic pressure achieved. In the 1950s and 1960s, many solid-state shock physicists followed this trend. However, materials response to shock loading is better described by the concept of stresses and strain rates, particularly when shear behavior cannot be neglected. The stress

²⁹³ J.D. ACHENBACH: *Dynamic effects in brittle fracture*. In: (S. NEMAT-NASSER, ed.) *Mechanics today*. Pergamon Press, New York *etc.*, vol. 1 (1972), pp. 1-57.

²⁹⁴ According to ANTOUN ET AL. { \Rightarrow 2003}, *mesomechanics* is a new approach used in fracture mechanics “to average the behavior of the individual voids or crack over a ‘relevant volume object’ representing a continuum point in space.”

²⁹⁵ T.W. BARBEE, L. SEAMAN, and R.C. CREWDSON: *Dynamic failure criteria of homogeneous materials*. Tech. Rept. No. AWFL-TR-70-99, Air Force Weapons Laboratory, Kirtland Air Force Base, NM (1970).

generated by a planar normal shock wave, which results in a uniaxial strain, can be decomposed into a hydrostatic component and a deviator.²⁹⁶

For over 30 years the shock community has grappled with how to measure the complete stress in and behind a shock wave. The most accurate shock wave measurements of pressure or stress have always been made in uniaxial stress, for example by planar impact. Such measurements typically provide stress, shock velocity, and particle velocity histories in the direction of shock propagation. The use of Lagrangian analysis yields stress/strain paths under uniaxial strain loading. In solid-state shock wave physics, correct measurements of stress histories are essential when testing numerical codes describing dynamic materials behavior. On the other hand, more refined numerical modeling has disclosed problems with measuring lateral shock stresses accurately (*see* Sect. 2.8.6).

A useful quantity to use to characterize a shock-compressed solid is the strain rate, since the response of a solid is dependent on the rate at which strain occurs {EXPLOMET 80 \Rightarrow 1980}. The global 1-D strain rate is defined as the rate of change of strain ϵ with time t , given by

$$d\epsilon/dt = 1/L \times dL/dt \approx 1/L \times \Delta L/\Delta t = v/L,$$

where L is the initial length, ΔL is the elongation, and v is the speed of deformation. At high rates, many materials deform by a different mechanism to that which occurs at low rates. High strain rates enter into most fracture, impact, erosion and shock loading situations. Depending on the method applied, strain rates obtainable in practice range from about $10^1 - 10^2 \text{ s}^{-1}$ (Charpy test and Izod test) to about 10^3 s^{-1} (split-Hopkinson pressure bar) up to 10^7 s^{-1} (high explosives, hypervelocity impact). Extreme strain rates of up to some 10^9 s^{-1} are possible in thin targets subjected to irradiation from ultrahigh-power laser pulses of picosecond duration.

With continuous technical improvements in the generation and recording of flash X-ray diffraction patterns at submicrosecond timescales, this promising diagnostic method was first successfully applied in the 1970s to shock-compressed materials. This allowed the interpretation of the physical quantity “strain rate” – originally introduced to characterize dynamic loading in the macroscopic world – to be extended to the microscopic regime too: in a crystal lattice the uniaxial compression of the unit cell with interplanar spacing d , caused by a shock wave with rise time $\Delta\tau$, is given by $\Delta d/d$,

and the corresponding strain rate $d\epsilon/dt$ is approximately given by

$$d\epsilon/dt \approx (\Delta d/d)/\Delta\tau.$$

A crystalline powder sample with a cubic lattice such as potassium chloride [KCl], when isotropically compressed by a planar 12-kbar shock wave with a rise time of some 10 ns {JAMET & THOMER \Rightarrow 1972}, would produce a microscopic strain rate on the order of $10^6/\text{s}$.

Off-Hugoniot States. *Principal Hugoniot* – i.e., the loci of single shock states for shocks of varying strength, starting from materials at normal density, atmospheric pressure, and room temperature ($\sim 300 \text{ K}$) – do not cover all states of interest in dynamic high-pressure physics. In order to obtain a more complete description of achievable states, it is necessary to access (p, v) -data of shock pressure p and density ρ (or specific volume $v = 1/\rho$) off the principal Hugoniot, which requires more sophisticated techniques and analytical methods. Traditionally, multiple or reflected shock waves have been used to achieve this goal. Such *off-Hugoniot* states are of interest, for example, when modeling

- ▶ materials under extreme conditions of pressure and temperature, such as those used in inertial confinement fusion studies;
- ▶ detonation products of solid high explosives; and
- ▶ planetary and stellar interiors at extreme conditions.

The impressive advancement achieved in experimental solid-state shock wave physics and improvements made in numerical modeling of dynamic materials response were mainly based on

- ▶ the availability of principal Hugoniot data for a large number of elements and compounds;
- ▶ the availability of more complete (p, v, e, T) equation of state data by extending principal Hugoniot data using the Mie-Grüneisen theory;
- ▶ the generation of well-defined and reproducible shock wave profiles;
- ▶ advances in submicrosecond measurements and visualization techniques;
- ▶ more refined analyses of thermodynamic states off the principal Hugoniot; and
- ▶ increased computer power, which permitted more detailed numerical material modeling.

Today, solid-state shock wave physics, now a well-established branch of high-pressure physics, provides a rich source of principal Hugoniot data for all kinds of solids: so-called “Hugoniot Data Banks” cover almost all solid

²⁹⁶ R.J. WASLEY: *Stress wave propagation in solids*. M. Dekker, New York (1973).

elements, a large number of technically relevant metal alloys, as well as many common minerals {WALSH, RICE, MCQUEEN & YARGER \Rightarrow 1957; VAN THIEL, SHANER & SALINAS \Rightarrow 1977}. In addition, solid-state shock wave physics has also placed a wealth of unique shock compression and diagnostic techniques at the disposal of scientists of other disciplines. This has significantly contributed not only to progress in traditional fields such as impact physics, ballistics and crash engineering, but also to new applications in geophysics, planetary sciences, seismology, fracture mechanics, laser fusion, materials science, and more recently also in medicine and biology.

2.5 PIERCING THE SOUND BARRIER: MYTH AND REALITY

“That is correct,” answered NICHOLL, “it is now 11 P.M. Thirteen minutes since we left America.”

“One question, however, still remains unsolved” said BARBICANE, “why have we not heard the bang when the Columbiad was fired?”

Less than a quarter of an hour later, BARBICANE stood up and shouted in a piercing voice: “I have it. Because our projectile flew faster than sound!”²⁹⁷

Jules VERNE
Paris 1869

COVERING large distances in a short time – *i.e.*, traveling at high speed, much faster than the fastest animals can move along – has been a dream of man since the earliest times, and has been the subject of numerous myths and legends { \Rightarrow Figs. 4.20–A, B}. Since until very recently man was incapable of achieving this goal through his own technology, he projected his ambition onto the supernatural powers of deities. For example, in early Greek mythology, the god HELIOS, who represented the Sun, was believed to traverse the heavens by day and to sail around the Earth (then viewed as a flat disc afloat on the river of Ocean) at night. His high-speed vehicles, which would have needed to be capable of supersonic velocities to perform this enormous task, were a

four-horse chariot and a mystical boat in the form of a golden bowl. Even now, only a few decades have passed since man first realized this dream, although the velocity required by HELIOS’ to sail around the world in a night has been exceeded by more than one order of magnitude {GAGARIN \Rightarrow 1961}.

Flying supersonically – let alone from one planet to another – was regarded as the wildest fiction at a time when the first flight of man with an “apparatus heavier than air” {VON LILIENTHAL \Rightarrow 1891} was still the pipe dream of a few outsiders. However, when the French author Jules VERNE wrote his fictional works *De la terre à la lune* (1865) and *Autour de la lune* (1872), substantial insights into supersonics had already been gained:

- ▶ the English military engineer Benjamin ROBINS { \Rightarrow 1746} had proven with his ballistic pendulum that a musket ball can fly supersonically and that drag increases dramatically when approaching the velocity of sound, a finding which the British gun expert and mathematician Charles HUTTON { \Rightarrow 1786} extended to cannon shots forty years later;
- ▶ the Austrian physicist Christian A. DOPPLER { \Rightarrow 1847} had pondered on wave generation by a supersonic object, thereby predicting that the object is surrounded by a conical wave, the “head wave” {E. MACH & SALCHER \Rightarrow 1886};
- ▶ the English physicist James Prescott JOULE and the Scottish engineer and physicist William THOMSON { \Rightarrow 1856} had predicted “aerodynamic heating” at high flight velocities;
- ▶ the U.S. ballistician General Thomas J. RODMAN { \Rightarrow 1864} had demonstrated with his 15- and 20-in. monster guns – so-called “columbiads”²⁹⁸ – that with his method of hollow casting guns of an even larger caliber should be realizable in principle; and
- ▶ the inventions of “mammoth powder” {RODMAN \Rightarrow 1857}, a new, progressive-burning propellant, and of a number of new high explosives with hitherto unprecedented detonation capabilities, such as guncotton {SCHÖNBEIN \Rightarrow 1845}, nitroglycerin {SOBRERO \Rightarrow 1846} and dynamite {A. NOBEL \Rightarrow 1867}, stimulated the fantasies of laymen as well as the expectations of experts that they could be applied for new, unprecedented propulsion purposes.

²⁹⁷ J. VERNE: *Autour de la lune*. J. Hetzel, Paris (1872). • In his work of fiction, three men and two dogs were shot to the Moon in a huge bullet by a monster cannon which had to achieve a minimum velocity of 11.2 km/s (when neglecting aerodynamic drag) in order to escape the Earth’s gravitational attraction. This so-called “escape velocity” became a much discussed quantity, and one that is still unattainable by single-stage powder guns. Jules VERNE was scientifically advised by his cousin Henri GARCET, who was a mathematics professor at the Ecole Henri IV in Paris.

²⁹⁸ The origin of the term “columbiad” is obscure. Some believe it was named after Joel BARLOW’s popular poem *The Columbiad* (1807), while others suggest that the term was applied to any cannon manufactured at Henry FOXALL’s Columbian Foundry near Washington, DC, which produced cannons and munitions in the period 1803–1854. • The term was widely used in the late 19th century and was also taken up early by the German encyclopedia *Meyers Konversations-Lexikon* (1894).

2.5.1 UNMANNED VEHICLES: FIRST DEMONSTRATIONS OF PRACTICABILITY

*We kept hoping that this rocket [the A-5, predecessor of the V2] would exceed the velocity of sound. The big question was: would there be stronger oscillations around the trajectory tangent due to the accompanying increase in aerodynamic drag and the variability of the center of gravity, thus causing the rocket to explode?*²⁹⁹

Walter DORNBERGER
Heeresversuchsanstalt Peenemünde
Peenemünde-Ost 1938

When aerodynamicists and aircraft designers began to ponder on the problems of supersonic flight, supersonics as a scientific discipline was already well advanced, and the following examples highlight illustrate the progress made in this field:

- ▶ German ballisticians had found the optimum shape for supersonic projectiles used in firearms, the famous S-bullet [Germ. *Spitzgeschoss*]. This pointed projectile, which was the fastest infantry projectile at that time ($v_0 = 893$ m/s), was adopted by many armies around the world {DWM \Rightarrow 1903};
- ▶ the German professor Ludwig PRANDTL at Göttingen University, together with his Ph.D. student Theodor MEYER, had studied the expansion of a supersonic flow around a corner, which resulted in the “Prandtl-Meyer theory of expansion” {MEYER \Rightarrow 1908};
- ▶ British studies on various airscrew geometries revealed a significant loss of thrust when the airscrew tips approached the velocity of sound {LYNAM \Rightarrow 1919; REED \Rightarrow 1922}. However, both theoretical and experimental requirements for the development of a supersonic airscrew {XF-88B \Rightarrow 1953; \Rightarrow Fig. 4.20–G} were still many years from being fulfilled;
- ▶ the British engineer Sir Thomas STANTON, who built the world’s first supersonic wind tunnel at NPL in Teddington {STANTON \Rightarrow 1921}, demonstrated that such a device is not only useful for aerodynamic drag studies of model projectiles, but that it is also useful for pressure measurements on scale models of aerofoils {STANTON \Rightarrow 1928};
- ▶ the Swiss aerodynamicist Jakob ACKERET devised a theory for thin sharp-edged supersonic aerofoils {ACKERET \Rightarrow 1925};
- ▶ the Hungarian-born U.S. aeronautical engineer Theodore VON KÁRMÁN and his Ph.D. student Norton B.

MOORE studied the aerodynamic drag of slender, spindle-like bodies at supersonic speed at CalTech’s Guggenheim Aeronautical Laboratory {VON KÁRMÁN & MOORE \Rightarrow 1932};

- ▶ the German aeronautical engineer Adolf BUSEMANN investigated the flow around aerofoils at supersonic speeds and observed that thin profiles are superior to thick ones {BUSEMANN & WALCHNER \Rightarrow 1933};
- ▶ the U.S. aeronautical engineers John STACK and Eastman N. JACOBS at NACA’s Langley Aeronautical Laboratory visualized the generation of a shock wave above an aerofoil in a transonic flow {STACK & JACOBS \Rightarrow 1933; \Rightarrow Fig. 4.14–L};
- ▶ Albert BETZ { \Rightarrow 1939}, a German professor of applied mechanics at AVA in Göttingen, gave the first experimental evidence of the superiority of the swept-back wing design, a concept previously proposed by BUSEMANN, who was originally derided for his idea {5th Volta Conf. \Rightarrow 1935}. However, the results of his studies, which were summarized in various top secret German patents, remained unknown outside Germany until the end of World War II; and
- ▶ in 1945, still before the first manned supersonic flight, the British applied mathematician M. James LIGHTHILL³⁰⁰ published a theory on the aerodynamic drag on finely pointed bodies of revolution. Obviously, the results from a new area of research, *gas dynamics of thin bodies*, had suggested to aircraft designers that a thin and slender design would be best for realizing supersonic velocities.

In the mid-1930s, issues relating to high-speed aviation were still of academic rather than of military relevance, and were freely discussed in the international aeronautical community {5th Volta Conf. \Rightarrow 1935}. However, shortly after 1935, a veil of secrecy was drawn over this subject. The vital importance of speed was impressively demonstrated in the numerous air battles during World War II. Although manned flight through the sound barrier didn’t appear to be close at hand in the early 1940s, various detrimental supersonic phenomena resulting from shock waves had already been observed in transonic aviation: in the United States, England and Germany, test pilots had experienced dramatic and dangerous increases in drag when their fighter planes had approached transonic speeds in dives. These increases in drag were accompanied by a loss of control which were obviously caused by aerodynamic compressibility effects and disturbed airflow {VON KÁRMÁN & DRYDEN \Rightarrow 1940; DITTMAR, Me-163

²⁹⁹ W. DORNBERGER: *V2 – der Schuß ins Weltall*. Bechtle, Esslingen (1952), p. 66.

³⁰⁰ M.J. LIGHTHILL: *Supersonic flow past bodies of revolution*. ARC Repts. & Mem. No. 2003. Ministry of Supply, H.M.S.O., London (1945).

⇒1941; GILKE, P-38 ⇒1941; MUTKE, Me-262 ⇒1945}. Some pilots of transonic planes lost control of their aircraft due to these shock waves, and barely escaped or were killed in a crash. Subsequent wind tunnel studies of model aircraft revealed the existence of shock waves when approaching the speed of sound. These shock waves indirectly caused tremendous forces capable of tearing the fuselage and wings apart.

Long before the birth of supersonic aeronautics, ballisticians and physicists had pondered on the reasons for the increased aerodynamic drag in the transonic regime {Sir NEWTON ⇒1687; ROBINS ⇒1746; HUTTON ⇒1786; BASHFORTH ⇒1864; GREENHILL ⇒1879; MAIYEVSKII ⇒1881; VIEILLE ⇒1900; BENSBERG & CRANZ ⇒1910}, some of them also attempting to find practical ways of diminishing wave drag. Obviously, these mysterious drag phenomena in the transonic regime impaired the ability to aim accurately and reduced the effective range and terminal velocity of shots when impacting the target. Their studies gave birth to *aeroballistics* – a new branch of ballistics dealing with the motion and behavior of projectiles, missiles and high-speed aircraft in the Earth's atmosphere.

Ballistic studies using flash photography performed in Austria {E. MACH & SALCHER ⇒1886} and England {BOYS ⇒1890} had already proved that bullets traveling at supersonic speed do not burst into pieces upon passing the sound barrier. However, piercing the “magic sound barrier” with a complex, lightweight vehicle structure, such as a full-scale manned airplane, appeared very risky to pilots and aerodynamicists, and many aircraft designers thought that it was an impossible task to manage the pressure forces generated by strong shock waves.

Flying at $M > 1$ should easiest to realize when the velocity of sound in the atmosphere is a minimum. Since the Mach number is defined as the ratio of the velocity of an object (such as a vehicle) to the velocity of sound, which decreases with increasing altitude, supersonic flight is most likely to be achieved at large altitudes.³⁰¹ Last but not least, the reduction in aerodynamic drag at such altitudes would also reduce the power required to break the “sonic wall.”

The development of an appropriate propulsion system played a central role in supersonic aviation. In the early 1940s, the most promising low-weight high-power propul-

sion was either the turbojet engine {He-178 ⇒1939; Me-262 ⇒1941} or the rocket motor {He-176 ⇒1939; Me-163 ⇒1944; ⇒Fig. 4.20–E}.

The proof of technical feasibility came from military rocketry. In the 1930s, General Walter DORNBERGER and Wernher VON BRAUN, two eminent rocket jet experts, had experimented with liquid-fuel-propelled rockets. With generous support provided by the German Army, they were directed to develop a guided rocket capable of transporting a 1-ton payload over a distance of 300 km at high supersonic velocities ($M > 4$). The aerodynamics of the 14-m-long A-4, which was reminiscent of the shape of an S-bullet but with four fins at its rear for control and stabilization at high speeds, was carefully studied using a number of rocket models in supersonic wind tunnels at the Heeresversuchsanstalt (HVA) Peenemünde, the German Rocket Center at the Baltic Sea. The results proved that stable flight could be achieved up to Mach 4 {HVA Peenemünde ⇒1939}. On October 3, 1942, the A-4, later named the V2, reached a velocity of $M > 4$, thereby covering a distance of almost 320 km and attaining a record height of 84.5 km – thus opening the door to the “realm” of space³⁰² {HVA Peenemünde ⇒1942; ⇒Fig. 4.20–C}. This test proved that a complex and delicate structure such as a large guided rocket could survive not only the passage through the dreadful transonic regime, but also the much-discussed aerodynamic heating that occurs during the supersonic phase. For the A-4, this phase lasted about six minutes,³⁰³ and the heating was estimated by VON BRAUN to be around 800 °C. During the experimental stage of the A-4 he had ordered the aluminum skin to be replaced with a 0.64-mm-thick steel sheet. This measure was also useful due to the general shortage of aluminum in Germany in those years. The nose of the rocket, initially intended to carry a 1-ton charge of TNT, was fabricated from 6-mm-thick steel sheet. However, in order to reach the required range of 250 km, the charge weight had to be reduced.³⁰⁴ Last but not least, the successful test at Peenemünde also first demonstrated in a spectacular manner an environmental problem connected with supersonic flight – the *sonic*

³⁰¹ The sound velocity u is a rather complex function of altitude h which resembles a zigzag line when plotted in the (h, u) -plane. In the range 0–10 km, u diminishes with increasing h , dropping from initially 340 m/s at sea level to a minimum value of 296 m/s at about 10 km. Then u remains almost constant over 10–20 km. At altitudes of 20–50 km, u increases steadily up to about 330 m/s at 50 km, before dropping steadily from 55–85 km to a value of about 275 m/s. See *Standard atmosphere* (ed. by NOAA). U.S. Govt. Printing Office, Washington, DC (1976).

³⁰² There is no definite boundary between the Earth's atmosphere and space. Above 500 km, in the exosphere, the Earth's atmosphere merges with the gases of interplanetary space, which some scientists consider to be the beginning of space. Others consider space to begin at an altitude of 160 km above the Earth's surface. According to the latter definition, the V2/WAC-Corporal test {⇒1949; ⇒Fig. 4.20–B} was the first successful project to launch a man-made vehicle into space.

³⁰³ In the test performed on October 3, 1942, the rocket engine operated for 58 seconds. Its radio transmitter worked for another five minutes until the rocket hit the Baltic Sea. See E. STUHLINGER: *Wernher VON BRAUN. Bechtle, Esslingen & München* (1992), p. 68.

³⁰⁴ W. DORNBERGER: *Peenemünde. Die Geschichte der V-Waffen*. Bechtle, Esslingen (1981), p. 246.

boom effect. Although this phenomenon was already known to ballisticians as the *ballistic crack*, the enormous size of the shock cone produced by a large object flying at high Mach number, which affects much larger areas on the ground than a projectile shot from a gun. The extent of the boom's "carpet" (the distance that it can be heard on each side of the aircraft's path along the ground, as well as its intensity), varies with the aircraft's height, speed, flight conditions, and with the prevailing atmospheric conditions. Typical maximum figures for SST aircraft ± 20 km from the ground are positive peak overpressures of between 50 and 100 Pa.³⁰⁵

The first vehicle to reach hypersonic velocities ($M > 5$) was the U.S. WAC (Women's Army Corps)-Corporal rocket { $\Rightarrow 1949$ }, developed by the Jet Propulsion Laboratory for the U.S. Army. Combined with a captured German V2 as a booster, it reached a velocity of $M > 7$ { \Rightarrow Fig. 4.20–D}. Beginning with the launch of the first Earth satellite {Sputnik 1 $\Rightarrow 1957$ }, space vehicles and probes were routinely accelerated to hypersonic velocities which ranged between 7.9 and 11.2 km/s (decreasing with altitude) in order to enter Earth's orbit.

2.5.2 MANNED VEHICLES: FROM VENTURE TO ROUTINE

*I do not imagine for one moment that man will be happy until he has conquered the "sonic barrier;" any experiments that we can perform to help him over the difficult threshold to supersonic flight will be of great value and may well save the lives of intrepid pioneers in this new and hazardous venture.*³⁰⁶

Earnest F. RELF
London 1946

*For me personally, however, I prefer a slower pace. I travel constantly by jet, but I like nothing better than to think of myself riding through the Paris boulevards as my parents did in old Budapest in a fiacre with a coachman and two horses.*³⁰⁷

Theodore von KÁRMÁN
CalTech
Pasadena, CA 1962

The first official demonstration of manned supersonic flight was provided on October 14, 1947 over Rogers Dry Lake in southern California by the USAF test pilot Charles YEAGER { $\Rightarrow 1947$ }. His test rocket plane, the Bell X-1, was attached to a B-29 mother ship and carried to an altitude of about 7,600 m. It then rocketed separately to about 12 km, reaching a velocity of $M = 1.06$ in level flight for 18 seconds. YEAGER's first supersonic flight reconfirmed previous observations that shock waves can vigorously shake a plane when approaching the sound barrier, but that beyond $M = 1$ the bumpy road turns into "a perfectly paved speedway" (YEAGER). His little plane, currently displayed at the Smithsonian National Air & Space Museum, looks rather clumsy according to our present understanding of supersonic aircraft design. It has neither sweptback wings {BUSEMANN $\Rightarrow 1935$ } nor the typical "thinness" of fuselage exhibited by later supersonic aircraft, the key to achieving low supersonic drag.

With his legendary flight YEAGER not only pierced the sound barrier physically, but he also cleared away the doubts and hesitations that were present in the minds of numerous contemporaries that human supersonic flight was not possible. The next achievements in high-speed flight occurred in rapid succession. On December 1953, in an improved version of his rocket-powered research aircraft, YEAGER became the first man to exceed Mach 2.³⁰⁸ On April 12, 1961, the Soviet cosmonaut Yuri A. GAGARIN { $\Rightarrow 1961$ } became the first human to fly hypersonically during the reentry of his Vostok 1 craft { \Rightarrow Fig. 4.20–J}, which began at $M > 25$. In the same year, the U.S. test pilot Robert WHITE {X-15 $\Rightarrow 1959$ & 1961} became the first pilot to reach hypersonic velocities ($M = 6$) with the X-15, the first hypersonic rocket plane { \Rightarrow Fig. 4.20–I}. In the years following, this remarkable aircraft reached an altitude of 67 miles (108 km) and attained hypersonic speeds of up to $M = 6.72$.

Beginning in the 1960s, various nations started to design a supersonic civil passenger plane (also known as "supersonic transport" or "SST" { \Rightarrow Fig. 4.20–H}): the American Boeing 2707-300 SST { $\Rightarrow 1968$ }; the Soviet Tupolev Tu-144 { $\Rightarrow 1968$ }; and the British/French Concorde { $\Rightarrow 1969$ }. By the early 1960s, the construction of passenger aircraft capable of speeds of 2,000 mph (939 m/s) appeared feasible. The chief issues were then to make such flights economically viable and to solve the special structural design problems involved. However, the environmental problems imposed on the population in the vicinity of airports and along

³⁰⁵ J.R. HASSALL and K. ZAVERI: *Acoustic noise measurements*. Brüel & Kjaer, Naerum, Denmark (1979), p. 220.

³⁰⁶ E.F. RELF: *Recent aerodynamic development* [34th Wilbur Wright Memorial Lecture]. J. Roy. Aeronaut. Soc. **50**, 421–449 (1946), p. 445. • Ernest F. RELF, F.R.S., was a staff scientist at the Aerodynamic Dept. of the National Physical Laboratory (NPL). In 1946, he became Principal of the new College of Aeronautics at Cranfield, U.K.

³⁰⁷ Th. VON KÁRMÁN and L. EDSON: *The wind and beyond*. Theodore VON KÁRMÁN, pioneer and pathfinder in space. Little, Brown & Co., Boston etc. (1967), p. 234.

³⁰⁸ Flying twice as fast as the velocity of sound was a technical challenge rather than a venture. Many laymen predicted further barrier effects at Mach 2. The question of what happens upon passing Mach 2 was also frequently asked by passengers who were using the Concorde for the first time.

the flight path were not seriously considered.³⁰⁹ Only the Concorde, a delta-winged jetliner designed for $M = 2$ and 144 passengers, achieved the goal of being used routinely for long-distance civil flights over a long period of time. Flights continued up to October 2003, when regular service was shut down. Although it had faced numerous environmental and economic problems since being put into service in 1976, the Concorde was a landmark in the design of supersonic aircraft, and its elegant futuristic appearance compared to other airliners always made it a spectacle.

The Tupolev TU-144 { \Rightarrow 1968} is another great example of the successful design of a supersonic liner; it even made its maiden flight prior to the Concorde. The TU-144 first flew passenger services in 1977, but unfortunately was not an economic success. One of the seventeen TU-144 built was modified to act as a supersonic flight laboratory {Tu-144LL \Rightarrow 1996}: NASA teamed with American and Russian aerospace industries over a five-year period in a joint international research program to develop technologies for a proposed future second-generation supersonic airliner to be developed in the 21st century.

The huge progress in supersonic flight, from YEAGER's first bumpy supersonic flight in a small research aircraft through to the smooth, almost unnoticeable passage of the huge Concorde through Mach 1, is perhaps best illustrated in an editorial published in 1971 in the American magazine *Aviation Week & Space Technology*.³¹⁰ Robert HOTZ, editor-in-chief of this journal, who participated in a demonstration flight at the 1971 Paris Air Show, wrote: "The most sensational aspect of flying as a passenger at Mach 2 in a supersonic transport is that there are no sensations whatsoever that differ from those in the current generation of subsonic jets... At Mach 1 there was a slight tremor that felt much the way an automobile coughs with a fouled spark plug... During the climb from 20,000 to 50,000 feet [6,096 to 15,240 m] and acceleration from Mach 1 to Mach 2, the flight was smooth as silk. When Aerospatiale test pilot Jean FRANCHI leveled off at 50,500 feet [15,392 m] and the Machmeter needle flickered just past two on the dial and steadied for normal Concorde cruise, one French journalist exploded in disbelief: 'I don't believe it,' he said. 'You must have a mouse inside that instrument that winds it up to Mach 2'" Later British Airways provided the following information for world travelers who had not yet experienced the event of passing the sound barrier in a Concorde, "There will also be a new Machmeter [\Rightarrow Fig. 4.20-H], which displays the aircraft

speed to passengers, and to celebrate the breaking of the sound barrier, a subtle wash of blue light will pass through the cabin as Concorde passes through Mach 1."

All the high-speed record flights mentioned above were performed at large altitudes; *i.e.*, under conditions of considerably reduced aerodynamic drag. However, for decades breaking the sound barrier with a land vehicle seemed to be an insurmountable task. On October 13, 1997 – one day before the fiftieth anniversary of YEAGER breaking the sound barrier in an airplane – the sound barrier was finally broken by a land vehicle. In northwestern Nevada, on the imperfectly smooth pavement of the salt flats of Black Rock Desert, the British jet test pilot Andy GREEN { \Rightarrow 1997} reached a speed of $M = 1.007$ with his jet car *ThrustSSC* { \Rightarrow Fig. 4.20-N}, a four-wheel vehicle provided with special high-speed rubber tires. Two days later, GREEN set the supersonic world land speed record of 766.609 mph ($M = 1.02$). The appearance of a bow shock wave in a photo of the car also proved its supersonic status { \Rightarrow Fig. 4.6-J}.

Land vehicles without wheels can potentially reach substantially higher velocities than this. Indeed, by the mid-1950s, rail-guided rocket sleds were pushing medium-scale test models weighing up to 91 kg up to speeds of Mach 3.4 {SNORT \Rightarrow 1955; \Rightarrow Fig. 4.20-M}. More recent developments of such test facilities have extended the range of test velocities available into the hypersonic regime. Presently, the Holloman High Speed Test Track (HHSTT) at Holloman Air Force Base in New Mexico is the largest facility capable of studying the effects of traveling at hypersonic speeds on full-scale models. A world speed record was achieved for a sled test recently when a 87-kg payload was accelerated up to a velocity of 2,885 m/s (about Mach 8.6) {Holloman Air Force Base \Rightarrow 2004}.

2.5.3 NEW CHALLENGES, NEW THREATS

The ultimate goal of high-speed flight would be the achievement of cruising velocities approaching the velocity of light (299,776 km/s). The term *astronautics*, used throughout the Western World, literally means navigation among the stars.³¹¹ Human voyages to other stars, however, are still science fiction and will not be attained in the foreseeable future.³¹² The

³⁰⁹ R.L. BISPLINGHOFF: *The supersonic transport*. *Scient. Am.* **210**, 25-35 (June 1964).

³¹⁰ R. HOTZ (ed.): *Martinis at Mach 2*. *Aviation Week & Space Technology* **94**, 7 (June 7, 1971).

³¹¹ In his book *The Wind and Beyond* (1967), Theodore VON KÁRMÁN appropriately wrote on page 238: "My friend Dr. DRYDEN has proposed that we substitute for astronautics the word cosmonautics, the science of travel in the cosmos, which is the Universe bounded by one star, our Sun. But the United States never did anything about this suggestion, perhaps because the Russians had already taken over the word."

³¹² *Non est ad astra mollis e terris via* ("There is no easy way from the Earth to the stars"), Lucius Annaeus SENECA (c.4 B.C. – c.A.D. 65).

light from the nearest star, *Proxima Centauri* – a member of *Alpha Centauri*, a triple star system in the southern constellation of Centaurus – takes a little longer than four years to reach the Solar System. Space vehicles propelled by nuclear fusion (fusing hydrogen into helium), a concept much discussed in the 1960s, would require a huge takeoff mass in order to attain velocities approaching the velocity of light. Similar problems also face laser-driven vehicles, where a train of high-energy laser pulses provided by huge terrestrial laser systems would be employed. These so-called “lightcraft” are still at the experimental stage and have only reached very modest velocities so far {MEAD & MYRABO \Rightarrow 1997}.

A terrestrial challenge also remains. The ultimate demonstration of human flight piercing the sound barrier is still pending: skydiving from the stratosphere in free fall, protected only by a pressurized “shockwave-proof” spacesuit. The U.S. Air Force pilot Joseph W. KITTINGER was said to be the first human to exceed the sound barrier in free fall. On August 16, 1960, he jumped from an open gondola suspended from a giant helium-filled balloon at 31.3 km. However, his jump record was unofficial and not sanctioned by the Fédération Aéronautique Internationale (FAI). Moreover, KITTINGER used a stabilizing parachute early in his jump, so technically his jump wasn’t considered free fall.

Another attempt was made by Michel FOURNIER, a retired French army officer and an experienced parachutist. He hoped to reach a maximum speed of 1,600 km/h (about Mach 1.5). His “Super Jump,” a free fall from a helium-filled balloon at an altitude of more than 40 km, was predicted to last about six minutes and 25 seconds. FOURNIER suggested that preparations for the jump have proven useful for several fields, such as aerospace medicine, and especially the technology associated with high-altitude rescue jumps for the crews of endangered space shuttles.^{313, 314} His attempt, planned for September 9, 2002 above Saskatchewan, Canada, had to be cancelled because of strong jet streams at 7,000 meters. Unfortunately, another attempt scheduled for August 25, 2003 at the North Battleford municipal airport, Saskatchewan, also failed because the helium-filled balloon (which was 25 stories high) burst during launch. In February 2006, he announced publicly to make another attempt to jump above the large Canadian plains, with the ambition to become the first man to cross the sonic wall in free fall. In September 2006, it was reported that his “Big Jump” will be postponed until the next years because of budget problems.

Achieving high cruising velocities under water is also another great challenge in terms of both research and technology. Supercavitation would allow naval weapons and vessels to travel submerged at hundreds of miles per hour. Laboratory studies performed in 1997 at the Naval Undersea Warfare Center (Newport, RI) demonstrated that a blunt-nose projectile launched underwater acts as a “cavitator” {NUWC \Rightarrow 1997; \Rightarrow Fig. 4.14–E}. Generating a large cavitation sheet that surrounds the whole projectile, it can move even faster than the speed of sound in water, thus producing a bow wave in water that is very similar to that of a supersonic shot in air {E. MACH & SALCHER \Rightarrow 1886}. Unknown to the Western World, the Soviet Union began to consider the idea of high-speed torpedoes decades ago.³¹⁵ In the late 1970s, the Russian Navy developed a rocket-powered supercavitating torpedo, the revolutionary *Shkval* [Russ. *шквал* meaning “squall”], being capable of 230 mph (about 102 m/s) – i.e., it was 4 to 5 times faster than other conventional torpedoes.³¹⁶

Future research into high-speed torpedoes would aim at speeds approaching or even surpassing the sound velocity. If such torpedoes were to be realized, they would potentially change the face of naval warfare.

2.6 EVOLUTION OF DETONATION PHYSICS

The kinetic theory of gases has for us artillerists a special charm, because it indicates that the velocity communicated to a projectile in the bore of a gun is due to the bombardment of that projectile by myriads of small projectiles moving at enormous speeds, and parting with the energy they possess by impact to the projectile... But in the particular gun under discussion, when the charge was exploded there were no less than 20,500 cubic centimetres of gas, and each centimetre at the density of explosion contained 580 times the quantity of gas, that is, 580 times the number in the exploded charge is $8\frac{1}{2}$ quadrillions, or let us say approximately for the total number eight-followed by twenty-four ciphers...³¹⁷

Sir Andrew NOBLE
London 1900

HISTORICALLY, investigations into the nature of shock waves have been closely related to the riddle of detona-

³¹³ *Skydiver to break sound barrier*. BBC News (Jan. 22, 2002); http://news.bbc.co.uk/2/hi/uk_news/england/1774130.stm.

³¹⁴ *Historic balloon jump deflates fast*. Saskatchewan News Network (Aug. 25, 2003); <http://freerepublic.com/focus/f-news/971578/posts?page=14>.

³¹⁵ S. ASHLEY: *Warp drive underwater*. *Scient. Am.* **284**, 62-71 (May 2001).

³¹⁶ *VA-111, Shkval (Squall)*. *Military Scope*, U.S.A. (Dec. 1, 2001); <http://www.periscope.ucg.com/mdb-smpl/weapons/minetorp/torpedo/w0004768.shtml>.

³¹⁷ From an evening lecture presented at the Royal Institution; see A. NOBLE: *Some modern explosives*. *Not. Proc. Meet. Memb. Roy. Inst. Lond.* **16**, 329-345 (1902).

tion, a highly transient thermochemical wave phenomenon. The correct interpretation of detonation was not achieved until the period 1880–1905 – almost 300 years after the invention of *gold fulminate*, the first “high explosive.” Detonation physics, a branch of fluid mechanics that has since grown into a huge field of its own, is closely related to thermodynamics, shock wave physics and chemical kinetics. Like shock wave physics, it relies strongly on high-speed – in many cases ultrahigh-speed – diagnostics. The following short sketches focus on some of the circumstances related to the step-by-step process of investigating the thermodynamic nature of chemical explosions and detonations.

2.6.1 BLACK POWDER: THE MAID OF ALL WORK

*Gunpowder, that old mixture, possesses a truly admirable elasticity which permits its adaptation to purposes of the most varied nature. Thus, in a mine it is wanted to blast without propelling; in a gun to propel without blasting; in a shell it serves both purposes combined; in a fuse, as in fireworks, it burns quite slowly without exploding. But like a servant for all work, it lacks perfection in each department, and modern science armed with better tools, is gradually encroaching on its old domain.*³¹⁸

Alfred NOBEL
London 1876

An *explosive* has been defined as a material – either a pure single substance or a mixture of substances – which is capable of producing an explosion through its own energy. Black powder or gunpowder is the most important “low” explosive. It is a combustible material that inherently contains all of the oxygen needed for its combustion; it burns but does not explode; and it produces a voluminous quantity of gas in a very short time which itself produces an explosion.

The origin of black powder has been disputed for centuries. It may have been imported from China, where it has long been used in fireworks and propelling rockets {Pien-ching \Rightarrow 1232; \Rightarrow Fig. 4.20–B}. Curiously, however, Marco POLO (1254–1324), the famous Italian traveler, never mentioned such a curiosity in his writings. It may have been discovered in northern Europe {GRAECUS \Rightarrow c.1250; BACON \Rightarrow 1267} or in Germany {SCHWARZ \Rightarrow c.1380}. Black powder was apparently first applied for ballistic purposes in the early 14th century both in Europe {GHENT \Rightarrow 1313/1314} and Arabia {SHEM ED DIN MOHAMED \Rightarrow 1320}. It may have been invented in Italy, because chemicals of the proper qual-

ity were mined there. Whatever the source, gunpowder became the “fuel” most commonly used to power firearms of all calibers over the centuries, and it partly replaced muscle in the rapidly growing mining industry. On the other hand, the rapidity of its transformation accompanied by the release of enormous dynamic forces challenged natural philosophers to understand the chemical reactions involved and to develop theoretical tools to optimize its use in ballistics.

Black powder consists of a mixture of potassium nitrate or ordinary saltpeter [KNO_3], sulfur and charcoal, and was first described in Europe by the English scholar Roger BACON { \Rightarrow 1267} for incendiary and explosive applications. The fuel in black powder is charcoal and sulfur, which are burned by the oxygen contained in potassium nitrate or sodium nitrate {DU PONT DE NEMOURS \Rightarrow 1858}. Black powder will not produce high pressures unless it is confined (e.g., in a hole for blasting purposes). Since it will only burn rapidly – it cannot detonate³¹⁹ – it cannot be used to generate shock waves. However, when used in firearms the hot gases of the reacting gunpowder are initially confined in the barrel but they are suddenly released at the moment when the projectile leaves the muzzle; this “uncorking effect” produces an impressive *muzzle blast*, which is actually a shock wave. By the 18th century, projectiles propelled by charges of gunpowder reached supersonic velocities {ROBINS \Rightarrow 1746; HUTTON \Rightarrow 1783}. In addition to the muzzle blast, supersonic shots always generate a *head wave*: a second shock wave which is carried along with the flying projectile.

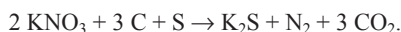
The first recorded nonmilitary use of black powder was for mining {Upper Leogra Valley \Rightarrow 1572; Schemnitz \Rightarrow 1627}, thus clearly illustrating that laborious methods of breaking ore or coal by hand could be replaced by the more economical and faster method of blasting. Black powder was also used for various spectacular construction jobs, such as for the first canal tunneling in France {Malpas Tunnel \Rightarrow 1679}. The application of black powder for blasting purposes in the mining industry was facilitated by the invention of the *Bickford fuse* or *safety fuse* {BICKFORD \Rightarrow 1831}. However, the need to produce potassium nitrate from certain soils imported from Spain, India, Italy and Iran limited its widespread use as an industrial explosive. With the invention of *B Blasting Powder* by the U.S. industrialist Lamot DU PONT { \Rightarrow 1858}, a modified black powder in which the expensive potassium nitrate

³¹⁸ A. NOBEL: *On modern blasting agents*. Am. Chemist 6, 60–68, 139–145 (1876).

³¹⁹ Depending on the grain size and the confinement, black powder burns at a relatively slow rate ranging between 560 and 2,070 ft/s (171–631 m/s). See *Blasters' Handbook*, E.I. du Pont, Wilmington, DE (1967), p. 26. Black powder, according to modern classification, is a “low” explosive. The arbitrary cut-off speed between “high” and “low” explosives” is 3,300 ft/s (about 1,000 m/s).

was replaced by the cheaper sodium nitrate³²⁰ or Chile saltpeter [NaNO₃] imported from Peru and Chile, black powder was widely accepted for industrial use. It was also used in one of the most difficult construction jobs of the 19th century, that of the first large railroad tunnel between France and Italy {Mont Cenis Tunnel ⇒ 1857}.

The nature of the reaction that takes place when gunpowder is fired has long fascinated the minds of chemists. Until around the year 1856, the metamorphosis of gunpowder was assumed to take place according to the equation found by the French chemist Michel E. CHEVREUL {⇒ 1825}



One gram of burning black powder produces about 718 cal, and over 40% of its original weight is transformed into hot gases at a temperature of almost 3,900 °C.³²¹

However, the accuracy of this simple equation was subsequently found to be doubtful. The first exact investigation of the compositions of both the gases and the solid products in the explosion was carried out at the University of Heidelberg by the German chemistry professor Robert W. BUNSEN {⇒ 1857} and his former student Léon SCHISCHKOFF, a Russian chemistry professor at the Artillery School of St. Petersburg. Starting from the concept of developing a “chemical theory of gunpowder,” they eventually discovered that a large number of salts are produced whose presence had not been detected before, besides the known constituents of smoke and solid residues. A comprehensive theory that explained the presence of the solid and gaseous residues after the explosion of gunpowder proved to be very difficult to devise. In the 1870s, Andrew NOBLE and Frederick A. ABEL {⇒ 1875}, two British military chemists, pursued the same idea of developing a theory for the firing of gunpowder. Although further progress was made, they arrived at essentially the same conclusion as BUNSEN and SCHISCHKOFF before, namely that the explosion products are not only very numerous, but also vary considerably in terms of their proportions according to the initial conditions (e.g., the levels of moisture and impurities, and the grain size), especially the pressure and therefore the temperature under which the explosion takes place. The German chemist Heinrich DEBUS {⇒ 1882}, one of BUNSEN’s oldest pupils and friends, resumed this subject in the early 1880s. He was the first to make the important observation that, depending on the mixing ratio of the ingredients, fired gunpowder

can also produce endothermic reactions that decrease the temperature of the explosion and therefore have a detrimental effect on the explosion. This finding further illustrated the complex nature of fired gunpowder.

As well as the chemical aspects of fired gunpowder, the physical ones were also discussed. The main questions for practical applications in artillery were:

- ▶ What is the maximum temperature of the powder burnt under ordinary pressure?
- ▶ What is the maximum pressure in the bore of a gun, and how long does it need to reach this pressure?
- ▶ How long does it take to convert the powder into gas?
- ▶ What is the maximum volume of the gaseous products generated during the explosion in relation to the initial volume?
- ▶ What is the “theoretical work” of gunpowder?

The answers to this catalog of complex problems, which were tackled both experimentally and theoretically by early chemists, ballisticians and physicists, led to somewhat contradictory results. They were discussed in the introduction of NOBLE’s and ABEL’s classical memoir on fired gunpowder {⇒ 1875}. For 1 kg of fired gunpowder, NOBLE and ABEL estimated that

- ▶ the temperature of the explosion was about 2,200 °C;
- ▶ the maximum pressure is 6,400 bar when the powder fills the space entirely;
- ▶ the permanent gases generated by the explosion occupy about 280 times the volume of the original powder at 0 °C and 1 bar; and
- ▶ the total work is 332,128 mkg* – a value which is about ten times smaller than the total work of 1 kg of coal.³²²

Black powder remained the sole explosive and propellant material until the mid-19th century, when nitroglycerin {SOBRERO ⇒ 1846} and cellulose nitrate {SCHÖNBEIN ⇒ 1845} were invented. However, it completely vanished from coal mining applications. Since exploding black powder could ignite firedamp, it was replaced by “permissible” explosives {Gelsenkirchen ⇒ 1880; MALLARD & LE CHÂTELIER ⇒ 1883; PENNIMAN ⇒ 1885} which produce a cooler flame and therefore a less intense flash of light {SIERSCH ⇒ 1896; ⇒ Fig. 4.17–G}. Today black powder is still used as an igniter for smokeless cannon propellants in large-caliber guns, and in fireworks, saluting charges and safety fuses.

The investigations of fired gunpowder were a tremendous challenge for early diagnostics. The biggest problems were (i) how to measure how long the combustion takes in the

³²⁰ Sodium nitrate can be synthesized from ammonia, which can be produced in large quantities by a process invented in 1908 by the German chemist Fritz HABER. This enabled Germany to manufacture explosives during World War I, when foreign supplies of nitrates were cut off.

³²¹ T.L. DAVIS: *The chemistry of powder and explosives*. Angriff Press, Las Vegas, NV (1972), pp. 42–43.

³²² For the meaning of kg* see ROUX & SARRAU {⇒ 1873}.

bore of a gun, and (ii) how to investigate how the combustion process is related to the motion of the projectile in the barrel – a classical problem in interior ballistics {DE LA GRANGE \Rightarrow 1793; A. NOBLE \Rightarrow 1894; \Rightarrow Fig. 4.17–L}. The principal task of interior ballistics is, given a particular gun, a particular shot, and a particular kind of powder, and a given load, to find

- ▶ the position and velocity of the shot;
- ▶ the mean pressure (and incidentally the temperature) of the gases in the gun; and
- ▶ the fraction of the powder burned,

all as functions of the time or of each other until the exit of the shot from the muzzle of the gun.³²³ Since the chemical and physical processes during the explosion all occur within the micro- to millisecond range, depending on the size of the reaction vessel and the grain size of the powder, their temporal resolution requires high-speed recording techniques, and so research in this field greatly stimulated advances in mechanical/electrical chronoscope technology. These technical challenges imposed on early gun propellant researchers – which were often combined with requirements to record the blast wave generated by the explosion as well – were an important “preschool” for tackling the even more difficult problem of how to record the much faster phenomena generated by the numerous new high explosives invented in the second half of the 19th century.

It is amusing to note here that black powder was also used in the past for another, very particular, civil purpose. Hundreds of years ago, black powder was used to test the alcohol content of whiskey: saturation with a 50% alcohol/water mixture will still allow black powder to catch fire; it burns with a clear blue flame. Both were mixed and ignited. If the black powder flashed, then it provided “proof” that it was good whiskey; *i.e.*, that it contained at least 50% alcohol. However, if there was too much water in the whiskey, the powder would be too wet to ignite: proof that it was *not* good whiskey. Thus, the 50% alcohol test became 100% proof that it was good whiskey, which is why it is now called “100-proof whiskey.”³²⁴ This unique application of black powder – though not related to shocks and explosions – provides further evidence of Alfred NOBEL’s view that black powder has long been “the maid of all work.”

2.6.2 THE RIDDLE OF DETONATION: STEPS TOWARD AN UNDERSTANDING

*Recent experiment has shown that the rapidity with which gun-cotton detonates is altogether unprecedented, the swiftness of the action being truly marvelous. Indeed, with the exception of light and electricity, the detonation of gun-cotton travels faster than anything else we are cognizant of...*³²⁵

Sir Frederick A. ABEL
Royal Artillery Institution
Woolwich 1873

Since the discovery of gold fulminate, man’s first high explosive, by the German alchemist Oswald CROLL { \Rightarrow 1608}, an impressive number of other explosive materials have been discovered by chance, or invented and modified by systematic investigations of industrial chemists to match particular requirements.

High Explosives. A high explosive (HE) is a compound or mixture which, when initiated, is capable of sustaining a detonation wave, producing a powerful blast effect. Examples of the most important HEs include silver fulminate {BERTHOLLET \Rightarrow 1786/1787}, picric acid {WOULFE \Rightarrow 1775}, mercury fulminate {HOWARD \Rightarrow 1800}, nitrogen trichloride {DULONG \Rightarrow 1812}, nitroglycerin {SOBRERO \Rightarrow 1846}, gun-cotton {SCHÖNBEIN \Rightarrow 1846}, dynamite {A. NOBEL \Rightarrow 1867}, tetryl (Wilhelm MICHLER & Carl MEYER 1879), ammonium nitrate (AN) {GLAUBER \Rightarrow 1659; PENNIMAN \Rightarrow 1885}, TNT {HAEUSSERMANN \Rightarrow 1891}, PETN {TOLLENS & WIGAND \Rightarrow 1891}, lead azide {CURTIUS \Rightarrow 1891}, and RDX {HENNING \Rightarrow 1899}.³²⁶

Shortly before World War II, the high explosive HMX (**high melting explosive**) or cyclotetramethylenetetranitramine – also known as “octogen” or “homocyclonite,” as well as by other names – was discovered. HMX is one of the densest and most heat-stable high explosives known, and together with RDX it is the basis for almost all modern high explosives. HMX [$C_4H_8N_8O_8$] is similar to RDX [$C_3H_6N_6O_6$] but it has a higher molecular weight (296.2) and a much higher melting point (256 to 281 °C). Moldable plastic explosives were also developed during World War II. In the early 1950s, the first polymer-bonded explosives were developed in the United States at LASL, (Los Alamos, NM).

³²³ A.G. WEBSTER: *Some new methods in interior ballistics*. Proc. Natl. Acad. Sci. U.S.A. **6**, No. 11, 648–659 (Nov. 15, 1920).

³²⁴ D.J. HANSON: *Alcohol glossary*, see definition of the term *proof* given in <http://www2.potsdam.edu/alcohol-info/AlcoholGlossary/GlossaryP.html>.

³²⁵ From an editorial note on Sir Frederick A. ABEL’s discovery made at Woolwich; see his article *The rapidity of detonation*. Nature **8**, 534 (1873).

³²⁶ For a review of the discoveries of various high explosives up to the late 1930s; see G. BUGGE: *Schieß- und Sprengstoffe und die Männer, die sie schufen*. Franckh, Stuttgart (1942).

Based upon HMX, and using Teflon as the binder, they were developed for projectiles and lunar active seismic experiments {Apollo 14 \Rightarrow 1971; Apollo 16/17 \Rightarrow 1972}.

The super high explosive CL-20 was first synthesized in the United States {NIELSEN \Rightarrow 1987}. Its extreme detonation velocity of 9,380 m/s (TNT: 6,930 m/s; HMX: 9,110 m/s) is of particular interest for achieving extremely high dynamic pressures, but this new highly energetic material is also currently being investigated for use as a rocket propellant. More recently, U.S. chemists synthesized another new type of very powerful high explosive, which they called “cubane,” a high-density hydrocarbon {ZHANG ET AL. \Rightarrow 2000}.

Generally, explosives are classified in terms of their explosivity:

- ▶ *low explosives* (such as black powder, the first known explosive) only deflagrate;
- ▶ *high explosives* detonate. They are usually subdivided into two categories: *primary high explosives* (such as some fulminates and lead azide), which detonate promptly upon ignition by a spark, flame, or heat generated by a light impact, and *secondary high explosives* (such as TNT, RDX, PETN), which require a detonator and, in some cases, a supplementary booster charge.

Explosives can also be classified in terms of their inner structure, which is useful for understanding the decomposition processes at the detonation front and for developing appropriate theoretical detonation models:

- ▶ *homogeneous explosives* include gases, liquids without bubbles or suspended solids, and perfect crystals of solid explosives. In these materials, planar shock waves uniformly compress and heat the explosive material. The release of chemical heat is controlled by the bulk temperature and pressure;
- ▶ *heterogeneous explosives* include liquids with bubbles or suspended particles and pressed or cast solids with voids, binders, metal particles, etc. The release of chemical heat by the initiating shock wave is controlled by local high-temperature and high-pressure regions, such as “hot spots” due to collapsing voids.

Detailed reviews of the large number of explosives and propellants available are given in special encyclopedias such as in the *Ullmann's Encyclopedia*³²⁷ and the *Encyclopedia of Chemical Technology*³²⁸ (these also include tabular compari-

sons of their physical properties), or in handbooks such as Dupont's *Blaster's Handbook* (1967) and the *LLNL Explosives Handbook* (1985).

Firing Devices. The greatest advance in the science of explosives after the discovery of black powder was certainly the invention of the *blasting cap* {A. NOBEL \Rightarrow 1863/1864}. Combined with the *safety fuse*, invented by the Englishman William BICKFORD { \Rightarrow 1831}, NOBEL's blasting cap provided a dependable means for detonating dynamite and the many other high explosives that followed it. His “detonators” contained mercury fulminate in a copper capsule which initiated the explosive reaction in a column of explosive by percussion rather than by the local heat from an electric spark or an electrically heated wire. From the 1880s onwards, a modification of this detonator (that still, however, worked according to the same principle of mechanical percussion) became widely used as an explosive signaling device. This so-called “railway torpedo” [Germ. *Knallkapsel*], which was provided with clips to fix it onto the railhead, was detonated when a vehicle passed by in order to attract the attention of railwaymen.

The blasting caps that followed were metal capsules containing a secondary explosive (such as TNT, tetryl or PETN) and a primary explosive (mostly mercury fulminate or lead azide). They are still used today to initiate secondary explosives. In the mid-1930s, the British chemist William PAYMAN and his collaborators visualized the detonation process for detonators using schlieren photography (\Rightarrow Fig. 4.16-X). Depending on the detonator geometry and the casing material, they observed jetting of gases and particles which are sent out ahead of the main shock wave, and are crucial for initiating detonation in the adjacent secondary explosive. The *safety detonator*, an “exploding bridgewire” version of the detonator, invented during World War II by the U.S. physicist Lawrence H. JOHNSTON { \Rightarrow 1944}, was one of the technical prerequisites for realizing the first nuclear implosion bomb {VON NEUMANN & NEDDERMEYER 1943; Trinity Test \Rightarrow 1945}. Since the safety detonator contains no primary explosive at all, it is extremely safe. The secondary explosive inside is initiated with submicrosecond accuracy via a shock wave generated by an exploding wire. This safety detonator has become an indispensable high-precision ignition tool in modern detonics.

The high detonation velocities of modern high explosives are an easy and very effective means of generating ultrahigh dynamic pressures {FOWLES & ISBELL \Rightarrow 1965}. However, the detonation velocity is not a constant quantity; i.e., it is dependent not only on the chemical composition and ambi-

³²⁷ J. BOILEAU, C. FAUQUIGNON, and C. NAPOLY: *Explosives*. In: (L. KAUDY, J.F. ROUNSAVILLE, and G. SCHULZ, eds.) *Ullmann's encyclopedia of industrial chemistry*. VCH, Weinheim/Bergstr., vol. A10 (1987), pp. 143-172.

³²⁸ V. LINDNER: *Explosives and propellants*. In: (M. HOWE-GRANT, ed.) *Encyclopedia of chemical technology*. Wiley, New York etc. (1991-1998), vol. 10 (1993), pp. 1-125.

ent physical conditions, but unfortunately also on the geometry of the high explosive bulk. For example, the detonation front in a stick diverges spherically as it progresses through the explosive, but when it reaches the stick's surface, the energy leaving the stick decreases the velocity locally. These so-called "edge effects" {G.I. TAYLOR \Rightarrow 1949} are particularly detrimental in all precision detonation configurations and were first noticed in the implosion assembly of the first atomic bomb (S. NEDDERMEYER 1943). Here, this phenomenon played an important role in the design of three-dimensional high explosive lenses made of fast- and slow-detonating high explosives that were used to shape the detonation wave in order to make it converge inward on a central point.

In the open literature, the use of a composite high-explosive charge for detonation wave shaping was apparently first discussed by the Englishman J.H. COOK { \Rightarrow 1948}, who used this method to engrave small designs on metal plates. Today detonation wave shaping is also important in explosive-formed projectiles (EFPs), a unique method in which a high explosive is used to simultaneously form a projectile and propel it up to hypersonic velocities. In the more sophisticated Multi-EFP concept, these munitions are set to explode ahead of the incoming threat, thus forming a dense "curtain" of high-velocity fragments within one millisecond.

By the year 1880, some of the explosives mentioned above were already being used for military and civil purposes. For example, mercury fulminate was used extensively. In 1835, France alone produced 800 million percussion caps that used mercury fulminate. However, the physico-chemical processes of explosion and detonation were not yet known. The increasing number of new explosive substances discovered in the following decades stimulated physicists and chemists to uncover the riddle of detonation, which was felt to be somehow closely related to the rapidly propagating mechanical (shock) wave created by the detonation.

In the period 1869–1874, the first detonation velocity measurements were carried out by the British chemist Sir Frederick A. ABEL. These studies, performed in long, confined charges of various high explosives, revealed unusually high velocities in the range of some thousands of meters per second. However, the rationale for detonation was not yet understood. The experiments of Henri J.B. PELLET³²⁹ and P. CHAMPION in France and Charles L. BLOXAM in England appeared to indicate that the detonating agent exerted some kind of vibratory action upon the particles of the substance

to be exploded. Studying the behavior of unconfined and confined charges, ABEL speculated that detonation in a high explosive might be transmitted by means of some "synchronous vibrations" {ABEL \Rightarrow 1869}, which BLOXAM, a professor of chemistry at King's College in London, called "sympathetic explosions." Shortly thereafter, the French chemist P.E. Marcellin BERTHELOT { \Rightarrow 1870} was the first to correctly assume that detonation might be caused by a strong moving mechanical shock – *une onde de choc* (a "shock wave") – but experimental proof of this was yet to appear {WENDLANDT \Rightarrow 1924}.

BERTHELOT's hypothesis, however, was not immediately accepted by the explosion research community, and the 1878 edition of the prestigious *Encyclopaedia Britannica*³³⁰ reads, "An explosive molecule is most unstable, certain very delicately balanced forces preserving the chemical and physical equilibrium of the compound. If these forces be rapidly overthrown in succession, we have explosion; but when, by a blow of a certain kind, they are instantaneously destroyed, the result is detonation. Just as a glass globe may withstand a strong blow, but be shattered by the vibration of a particular note, so it is considered by some authorities that, in the instance cited, the fulminate of mercury communicates a vibration to which the gun-cotton molecule is sensitive, and which overthrows its equilibrium; it is not sensitive to the vibration caused by the nitroglycerin, which only tears and scatters it mechanically." During this period, Hermann HELMHOLTZ's "theory of resonance" (1857) and the demonstration of resonance performed using his "Helmholtz resonator" were very popular among acousticians, and Heinrich HERTZ first demonstrated the detection of weak electromagnetic waves with a resonance circuit (1887), certainly one of the greatest triumphs for the mighty principle of resonance. However, the riddle of detonation in liquid and solid explosives couldn't be solved using this concept of resonance.

At this point, it is useful to look back on previous attempts to understand detonation in gases. The discovery of oxyhydrogen and its violent explosive properties {TURQUET DE MAYERNE \Rightarrow 1620; CAVENDISH \Rightarrow 1760s} stimulated not only a crude theory on the origin of earthquakes {LÉMERY \Rightarrow 1700; KANT \Rightarrow 1756}, but it also turned the interest of naturalists to other explosive gaseous mixtures, particularly to firedamp, which had been a hazard to miners since the beginning of hard coal mining in the 12th century. In the second half of the 19th century, coal mining increased tremendously in most European countries due to the rapid

³²⁹ H.J.B. PELLET and P. CHAMPION: *Sur la théorie de l'explosion des composés détonants*. C. R. Acad. Sci. Paris **75**, 210-214 (1872); *Explosions produced by high tones*. Phil. Mag. **46** [IV], 256 (1873).

³³⁰ W.H. WARDELL: *Explosives*. In: *Encyclopaedia Britannica*. Black, Edinburgh (1878), vol. 8, pp. 806-813.

adoption of steam engines for use in ironworks, the production industry, and advances in railroad and shipping traffic. In addition, hard coal was increasingly used as a fuel in homes and for producing city gas. For example, in England the productivity of hard coal mining increased from ten million tons at the beginning of the 19th century to 184 million tons in 1890.³³¹ Black powder, first used in the 16th century as a blasting agent in mines, was also applied in underground coal mining due to its relatively gentle, heaving action, leaving the coal in a good position for rapid loading. However, black powder has a dangerous tendency to ignite coal dust and coal gas, which mostly consists of methane. As a consequence, many disastrous mine explosions occurred with a large loss of life {ABEL \Rightarrow 1881}.

Firedamp Explosions. The scientific investigation of firedamp explosions was initiated by Sir Ralph MILBANKE { \Rightarrow 1813}, founder and first chairman of the Society for Preventing Accidents in Coal Mines. He asked the English chemist Humphry DAVY to develop a safe lamp for working in coal mines. DAVY { \Rightarrow 1816}, partly supported by his assistant Michael FARADAY, analyzed the explosivity of firedamp and discovered that the critical mixture for explosion is 9% methane and 91% air. The result of DAVY's studies was the "Davy lamp" { \Rightarrow Fig. 4.21–B}, certainly his most famous invention. Unfortunately, however, this lamp could only partly mitigate the risk of explosion accidents. For example, William GALLOWAY { \Rightarrow 1874}, a British mine inspector, demonstrated that the blast wave generated in a firedamp explosion forces the flame through the mesh of a Davy-type safety lamp. There were also other sources of open fire, such as those resulting from explosives used for blasting purposes, one of the oldest and most important civil applications of explosives since the 16th century.

DAVY's combustion studies, though worthwhile from a practical point of view, could not solve the riddle of the nature of an explosion. Similarly, studies carried out almost 50 years later by Robert BUNSEN { \Rightarrow 1857 & 1867}, a German chemist at the University of Heidelberg, were only partly successful. BUNSEN, cofounder of chemical spectroscopy, and an international authority on analytical chemistry, who turned the analysis of gases into an exact science, measured the strength and rate of combustion of various explosive gaseous mixtures, including oxyhydrogen. However, he used an experimental set-up that could not provoke detonation, only deflagration, which is a much slower

chemical reaction than detonation by several orders of magnitude.

Coal Dust Explosions. Dust explosions, certainly the oldest type of man-made explosion, frequently occurred in flour mills and bakeries {MOROZZO \Rightarrow 1785}, and later also in metal powder works {Bethlehem Zinc Works \Rightarrow 1854}. Such explosions stimulated various hypotheses that coal-dust-laden air might cause explosions in coal mines in an analogous manner {FARADAY & LYELL \Rightarrow 1845; RANKINE & MACADAM³³² 1872}. Eventually, a series of tragic firedamp explosions in the French coal mining industry {Jabin de Saint-Etienne \Rightarrow 1876} led to the foundation of the French Firedamp Commission { \Rightarrow 1877} with the objective to scientifically investigate possible causes of these explosions and to suggest efficient and economic countermeasures. Additional mining accidents due to firedamp explosions in France, England and the United States soon afterward (some of them probably also produced by the presence of coal dust) initiated the foundation of similar national institutions in these countries.

Detonation Wave. In Paris at the Collège de France, the chemist P.E. Marcellin BERTHELOT initiated comprehensive studies on the mechanism of detonation in gases. These investigations were carried out together with Paul VIEILLE, a skilful chemist and explosives specialist at the Central Laboratory of the Service des Poudres et Salpêtres in Paris, and they revealed

- ▶ that an explosive wave – later generally termed a *detonation wave* – exists in explosive gaseous mixtures and propagates at a tremendous speed of up to 2,500 m/s; and
- ▶ that the propagation velocity only depends on the mixture composition, not on the tube diameter, as long as that diameter is not too small {BERTHELOT \Rightarrow 1881; BERTHELOT & VIEILLE \Rightarrow 1882}. This explained BUNSEN's failure to provoke detonation in narrow tubes {BUNSEN \Rightarrow 1867}.

Another pair of prominent researchers were also enlisted by the French Firedamp Commission: François E. MALLARD, a professor of mining engineering, and Henry L. LE CHÂTELIER, a chemistry professor who both taught at the distinguished Ecole des Mines in Paris. They were asked by the Commission to examine the best means of guarding against firedamp explosions in mines. This led to a series of investigations on the specific heat of gases at high tempera-

³³¹ Meyers *Conversationslexikon*. Bibliographisches Institut, Leipzig & Wien, vol. 16 (1897), pp. 374–375.

³³² S. MACADAM: *On flour-mill fire-explosions*. Proc. Phil. Soc. Glasgow 8, 280–288 (1873).

tures, the ignition temperatures and the flame propagation velocities of gaseous mixtures {MALLARD & LE CHÂTELIER \Rightarrow 1881}. They first recorded the propagation of an explosive wave in a long tube with a rotating drum camera – a milestone in detonation diagnostics. Most surprisingly, they observed that the transition from combustion to detonation occurs suddenly, and that the detonation velocity is comparable to the velocity of sound of the burnt detonation products {MALLARD & LE CHÂTELIER \Rightarrow 1883}.

Chapman-Jouguet (CJ) Theory. The results from these two French teams prompted a new era in understanding explosions, and promoted the first theory of detonation. A simple and convincing explanation for the “explosive wave” was given by the English chemist David L. CHAPMAN { \Rightarrow 1899}, who – stimulated by previous English studies on detonation {SCHUSTER \Rightarrow 1893; DIXON \Rightarrow 1893} – assumed that the chemical reaction takes place due to a sharply defined front sweeping over the unburnt gas and changing it instantaneously into burnt gas { \Rightarrow Fig. 4.16–S}. The term *explosive wave* was understood by CHAPMAN “to limit the space within which chemical change is taking place. This space is bounded by two infinite planes. On either side of the wave are the exploded and unexploded gases, which are assumed to have uniform densities and velocities.” In comparison to a normal shock wave with its discontinuous transition from uncompressed to compressed gas across the shock front, the detonation front additionally separates two chemically different states of unburnt and burnt gases. A detonation wave is therefore also called a “reactive shock wave.” When CHAPMAN put forward his pioneering hypothesis on detonation, little was known about the atomic processes of initiating detonation. Avoiding a discussion of this problem, and instead focusing on the macroscopic behavior of explosive waves, he wrote, “How the true explosive wave is actually generated in practice is a question without the scope of the present investigation. In order to avoid the discussion of this point, I shall substitute for it a physical conception, which, although unrealizable in practice, will render aid in illustrating the views here advanced.”

CHAPMAN’s assumption was also made independently by the French engineer and mathematician Emile JOUGUET { \Rightarrow 1904/1906 & 1917}, a professor at the Ecole des Mines in Saint-Étienne. The so-called “Chapman-Jouguet (CJ) theory” – a term apparently later coined at the U.S. Bureau of Mines {LEWIS & FRIAUF \Rightarrow 1930} – independently evolved in Russia {MIKHEL’SON \Rightarrow 1890}, France {JOUGUET \Rightarrow 1904/1906; CRUSSARD \Rightarrow 1907; JOUGUET \Rightarrow 1917}, and

England {SCHUSTER \Rightarrow 1893; DIXON \Rightarrow 1893; CHAPMAN \Rightarrow 1899}. The CJ theory, which treats the detonation wave as a discontinuity with an infinite reaction rate, assumes that the hot products of the combustion wave act as an expanding hot-gas piston that accelerates the unburnt mixture ahead, thereby forming a sharply defined front called the “explosive wave” (or, in modern terms, the “detonation wave”), which sweeps over the unburnt gas { \Rightarrow Fig. 4.16–S}. Furthermore, the understanding of detonation phenomena was significantly advanced owing to the classical work of the French physicist Louis CRUSSARD { \Rightarrow 1907}.

The CJ theory does not require any information about the chemical reaction rate; *i.e.*, about the chemical kinetics. More details about the evolution of this first detonation model can be found in the CHRONOLOGY. The conservation equations for mass, momentum and energy across the one-dimensional wave give a unique solution for the detonation velocity (or CJ velocity) which correspond to the *Mikhel’son line* {MIKHEL’SON \Rightarrow 1893} or *Rayleigh line* {Lord RAYLEIGH \Rightarrow 1878}. In the pressure-volume diagram the Mikhel’son-Rayleigh-line corresponds to the CJ solution which is tangent of the Hugoniot curve for the burnt gas: the tangent line inclination to the Hugoniot curve is the local sound speed squared in the burnt gas. A higher detonation velocity than the CJ detonation velocity is possible by constructing an explosive in a two-layer arrangement and then using the so-called “channel effect” {BAKIROV & MITROFANOV \Rightarrow 1976}.

Zel’dovich-von Neumann-Döring (ZND) Theory. The assumption of a sharp detonation front is an idealization, and the Chapman-Jouguet theory, which treats the detonation wave as a discontinuity with an infinite reaction rate, was later refined by introducing a three-layer model of the detonation front { \Rightarrow Fig. 4.16–S}. This improved model, which also takes the reaction rate into account, was advanced independently during World War II in the former Soviet Union by the chemist Yakov B. ZEL’DOVICH (1940), in the United States by the mathematician John VON NEUMANN (1942), and in Germany by Werner DÖRING, a theoretical physics professor at the Reichsuniversität Posen {Secret Workshop “Probleme der Detonation” \Rightarrow 1941; DÖRING \Rightarrow 1943}. Today known as the “Zel’dovich-von Neumann-Döring (ZND) theory,” it provides the same detonation velocities and pressures as the CJ theory; the only difference between the two models is the thickness of the wave {ZEL’DOVICH \Rightarrow 1940}. In this so-called “ZND model,” the detonation process consists of a shock wave that takes the material from its initial state to a “von Neumann” spike point on the unreacted

Hugoniot. The ZND reaction zone is traversed by proceeding down the detonation Rayleigh line from the spike point to the CJ condition; *i.e.*, the fully reacted state.

The ZND model was originally derived for a one-dimensional steady state detonation wave in a gaseous explosive, and modifications of this model have since been proposed by numerous detonation researchers in order to get a better match to experimental conditions. For example, a more refined *one-dimensional nonequilibrium ZND model* was developed {TARVER \Rightarrow 1982} that also includes the thermal relaxation processes which precede and follow the exothermic chemical reconstitution reactions that take place in condensed explosives. Since the 1950s, numerous theoretical and experimental studies have been performed in order to precisely determine the CJ pressure and the length of the reaction zone in a detonating high explosive {DUFF & HOUSTON \Rightarrow 1953; DEAL \Rightarrow 1957}. For solid high explosives, the reaction zone length – *i.e.*, the distance from the spike point to the CJ state – is very short; for the high explosive HMX, this amounts to only some hundreds of microns, which corresponds to a reaction zone time of only a few tens of nanoseconds {GUSTAVSEN ET AL. \Rightarrow 1997}.

The CJ and the ZND theories provide a macroscopic picture of the mechanism of detonation, but they cannot describe the chemical processes of detonation at the molecular level. Obviously, in order to “wake up” or “trigger” an explosive molecule using an impacting shock wave, the energy that must be deposited by the shock wave to initiate exothermic chemical decomposition must be distributed to the vibrational modes of the explosive molecule within the appropriate time window to form a detonation wave.³³³

Complex Detonation Processes. Numerous experimental studies have revealed that many self-sustaining detonations – *i.e.*, detonations furnished by the driving energy of the chemical reaction – are not strictly one-dimensional, but that they contain transverse waves which may be quite strong, leading to a *periodic cell structure* {BONE ET AL. \Rightarrow 1936}. The Los Alamos detonation physicists Wildon FICKETT³³⁴ and William C. DAVIS gave an intuitive picture of how cellular structures might arise from a grid of regularly spaced perturbations interacting with each other in terms of individual Mach reflections {VON NEUMANN \Rightarrow 1943}. They wrote, “The key feature of the structure is the transverse wave, an

interior shock joined to the leading shock in the conventional three-shock configuration. The Mach stem and the incident shock are part of the leading shock, and the transverse wave is the reflected shock. The transverse waves move back and forth across the front. Groups of them moving in the same direction take up a preferred spacing on the order of 100 reaction-zone lengths. They are not steady waves, but are continually decaying, and stay alive only by periodic rejuvenation through collision with other transverse waves moving in the opposite direction.”

Transverse waves are particularly strong in *spinning detonation*, which is often observed in near-limit mixtures in round tubes {CAMPBELL & WOODHEAD \Rightarrow 1926; BONE & FRASER \Rightarrow 1929}.³³⁵ Based upon images obtained by different high-speed recording techniques, the two-dimensional cell structure is now fairly well understood, but the processes that occur in the three-dimensional reaction zone and the wave structure behind the front are difficult to resolve optically. With the advent of powerful computers, so-called “supercomputers,” the riddle of three-dimensional structures of detonation waves has also been tackled through numerical simulation {FUJIWARA & REDDY \Rightarrow 1993}.

Evolution of Chemical Kinetics. The classical chlorine-hydrogen explosion – a puzzling photochemical-induced reaction discovered by the French chemists Joseph-Louis GAY-LUSSAC and Louis J. THÉNARD { \Rightarrow 1809} – was investigated in more detail by the English chemist David L. CHAPMAN in the period 1909–1933. The German chemist Max E.A. BODENSTEIN { \Rightarrow 1913} had first advanced the concept of reactive intermediates as part of a “chain reaction” [Germ. *Kettenreaktion*], a term which he coined. In 1918, Walther H. NERNST, another German chemist studying photochemistry, postulated his “atom chain reaction theory.” This assumed that once the energy of a quantum has initiated a reaction in which free atoms are formed, these formed atoms can themselves decompose other molecules, resulting in the liberation of more free atoms, and so on... Both of their concepts explained detonation not as an instantaneous, single-stage chemical reaction, but rather as branched chain reactions that pass through various short-living intermediate states.

Their findings stimulated the evolution of *chemical kinetics*, a new and exciting branch of physical chemistry that deals with the rates and mechanisms of chemical reactions {SEMENOV & HINSHELWOOD 1928; Nobel Prize for Chemistry \Rightarrow 1956}.

³³³ C.M. TARVER: *What is a shock wave to an explosive molecule?* In: (M.D. FURNISH, N.N. THADHANI, and Y. HORIE, eds.): *Shock compression of condensed matter – 2001*. AIP Conference Proceedings, Melville, NY (2002), pp. 42–49.

³³⁴ See FICKETT & DAVIS { \Rightarrow 1979}, pp. 291–300.

³³⁵ An *explosion limit* usually refers to the range of pressure and temperature for which an explosive reaction at a fixed composition mixture is possible.

Combustion theory, a more general discipline which grew steadily in importance in the 20th century, also tackled the difficult problem of understanding explosion processes in order to provide an insight into the fundamentals of chemical kinetics. It turned out that two qualitatively different mechanisms can produce explosions in homogeneous combustion systems:

- ▶ one mechanism is that of a *thermal explosion*, in which heat released by the reaction raises the temperature. This, in turn, accelerates the rate of heat release;
- ▶ the other mechanism is that of a *branched-chain explosion*, in which large numbers of highly reactive intermediate chemical species – so-called “free radicals” – are produced in the combustion reactions, and these radicals accelerate the reaction rate.

The increasing number of studies aimed at improving our fundamental understanding of all aspects of combustion from a theoretical and a mathematical (numerical) modeling perspective led to the establishment of the journal *Combustion Theory and Modelling* {⇒1997}.

Since the invention of the four-stroke internal combustion engine by the German mechanical engineer Nikolaus A. OTTO in 1876, and its widespread use in automobiles (which were first invented in 1885–1886 by Carl BENZ and Gottlieb DAIMLER), the study of *knocking* (or *pinging*) has occupied generations of chemists {NERNST ⇒1905}. This detrimental detonation phenomenon, which occurs during combustion in an instantaneous, uncontrolled manner, reduces both the power output and the lifetime of the engine. Detailed studies that made use of the basic knowledge of detonation obtained previously from investigations of firedamp explosions showed that an explosive, premature self-ignition of the fuel takes place in Otto-engines before the flame front, thus leading to a detonation wave. Knocking can be prevented in internal combustion engines through the use of high-octane gasoline, the addition of lead (which increases the octane rating) or iso-octane additives to the gasoline, or by retarding spark plug ignition.

2.6.3 DETONICS: THE KEY TO ULTRAHIGH SHOCK PRESSURES, AND NEW APPLICATIONS

High explosives played an important role in the evolution of shock wave physics, particularly in the study of solid matter under high dynamic pressures. At first, simple arrangements with an explosive in contact with the test target were used.

This straightforward technique was later refined by employing an explosive lens {J.H. COOK ⇒1948}, which allowed the controlled generation of planar shock waves for the first time, and the measurement of Hugoniot data from one-dimensionally shocked materials {GORANSON ET AL. ⇒1955; DICK ⇒1970}. The method was further improved by using an explosively driven plate arrangement, the “flyer plate method” {MCQUEEN & MARSH ⇒1960}, which allowed the generation of shock pressures of up to 2 Mbar. In the 1950s, Soviet researchers developed cascade detonation devices incorporating spherical flyer plates which allowed the production of ultrahigh pressures {AL'TSHULER ⇒1996}. Another method of generating high dynamic pressures using high explosives is the application of the Mach effect, a nonlinear superposition of two obliquely interacting shock waves {AL'TSHULER ET AL. ⇒1962; FOWLES & ISBELL ⇒1965; NEAL ⇒1975; ⇒Figs. 4.13–H, L}.

As solid-state shock wave physics has evolved further, other, more appropriate, methods of generating very high dynamic pressures in the laboratory that do not require high explosives have been developed. Prominent examples include:

- ▶ hypervelocity planar impact methods that use the light-gas gun {CROZIER & HUME ⇒1946}, the railgun {RASHLEIGH & MARSHALL ⇒1978}, or the electric gun {STEINBERG ET AL. ⇒1980};
- ▶ pulsed radiation methods that use giant laser pulses {ASKAR'YAN & MOROZ ⇒1962}, or high-intensity pulsed soft X-ray pulses;
- ▶ pulsed beams of electrons, neutrons or ions {BLUHM ET AL. ⇒1985}; and
- ▶ a strong flux of neutrons from an underground nuclear explosion contained within rocks {TRUNIN ET AL. ⇒1992}, which has been the only type of nuclear test permitted since the Moscow International Nuclear Test Ban Treaty came into effect {⇒1965}.

However, high explosives are still an inexpensive and indispensable way of producing special high-pressure effects or other physical effects in a simple way. For example, they proved very useful for generating very high magnetic fields by *magnetic field compression* {TERLETSKII ⇒1957; FOWLER ET AL. ⇒1960}, a promising method of generating strong current pulses when operating pulsed radiation sources such as high-intensity pulsed laser radiation, electromagnetic microwaves and bursts of γ -rays, which (amongst other applications) can also be used in special experimental arrangements to generate shock waves under extreme conditions.

The *shaped charge cavity effect*, a curiosity in the history of explosives and a staple in detonics, has proven its wide applicability in both military and civil circles. This unique effect was originally discovered in charges without liner, first in a charge of black powder {VON BAADER \Rightarrow 1792} and then also in high explosives {VON FÖRSTER \Rightarrow 1883; MUNROE \Rightarrow 1888}, and it is particularly striking when a metal liner is used. The resulting hypervelocity jet of molten liner material is capable of penetrating even thick steel plates. This *shaped charge lined cavity effect* was invented independently by various detonation researchers in the late 1930s {THOMANEK \Rightarrow 1938}, and it immediately gained the greatest importance during World War II as an inexpensive but highly effective armor-piercing weapon. The “bazooka” [Germ. *Panzerfaust*], an anti-tank device, was based on the shaped-charge concept. Used as the “poor man’s high-velocity gun,” the shaped charge has become a standard weapon in many military arsenals. Shaped charges are also used to perforate oil-well casings {MCLEMORE \Rightarrow 1946; \Rightarrow Fig. 4.15–L} – this has long been their main civilian application – as well as for tapping open-hearth steel furnaces. This important cavity effect was studied in great detail (particularly the jet formation) both analytically {BIRKHOFF & G.I. TAYLOR \Rightarrow 1948} and experimentally using flash radiography {STEENBECK \Rightarrow 1938; \Rightarrow Fig. 4.8–F}. In addition, flash X-ray diffraction provided the first insights into the fine structure of the high-velocity jet of the liner material {JAMET & THOMER \Rightarrow 1974; GREEN \Rightarrow 1974}.

Blasting describes the process of reducing a solid body, such as rock and ice, to fragments. Besides its various applications in the military, this method is also used for civil purposes, such as to move large masses of earth when building canals (\Rightarrow Fig. 4.16–K) and dams, for tunneling {Musconetcong Tunnel \Rightarrow 1872} and other construction works, and to demolish natural obstacles {Hell Gate \Rightarrow 1885; Ripple Rock \Rightarrow 1958} or man-made structures {Helgoland Blast \Rightarrow 1947}. Historically, black powder was used as early as the 17th century for mining purposes. However, beginning with the invention of dynamite {NOBEL \Rightarrow 1867}, black powder was increasingly replaced by more efficient high explosives, and since about 1900 so-called “permissible explosives” have been employed, which considerably reduce the chances of triggering firedamp explosions. In the oil industry, explosives are also used for *oil well shooting* {ROBERTS \Rightarrow 1864} and to “snuff out” oil well fires {KINLEY \Rightarrow 1913; \Rightarrow Fig. 4.15–K}. Other large fields in which high explosives are applied include *explosive working* {RINEHART & PEARSON \Rightarrow 1963; \Rightarrow Figs. 4.15–I, J}, the *shock synthesis* of new

materials {PRÜMMER \Rightarrow 1987}, and *explosion seismology* (see Sect. 2.7.1).

2.6.4 NUCLEAR AND THERMONUCLEAR EXPLOSIONS: THE ULTIMATE MAN-MADE SHOCK PHENOMENA

*As the Director of the Theoretical Division at Los Alamos, I participated at the most senior level in the Manhattan Project that produced the first atomic weapons. Now, at the age of 90, I am one of the few remaining senior project participants... In my judgment, the time has come to cease all physical experiments, no matter how small their yield, whose primary purpose is to design new types of nuclear weapons, as opposed to developing peaceful uses of nuclear energy. Indeed, if I were President, I would not fund computational experiments, or even creative thought designed to produce new categories of nuclear weapons...*³³⁶

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Ithaca, NY 1997

A proper historical account of the Manhattan Project (\Rightarrow 1942) and the development of the first atomic bombs – even one confined solely to the shock and detonation research that took place during the Project – is beyond the scope of this book. However, some of the most important achievements are listed in the CHRONOLOGY, and the most important steps that led to the first atomic bombs based upon uranium and plutonium will be summarized in this chapter. Their construction presented many difficulties, and such a task was actually considered to be impossible by many renowned physicists of that time. A few examples of problems related to nuclear blast wave effects {G.I. TAYLOR \Rightarrow 1941 & 1944; VON NEUMANN \Rightarrow 1943} and precise triggering of multiple detonations {JOHNSTON \Rightarrow 1944} are also given in the CHRONOLOGY.

The development, testing and use of the first nuclear weapons are subjects that have been treated extensively in the literature and widely illuminated from scientific, technical,

³³⁶ From an open letter by Prof. em. Hans A. BETHE – recipient of the 1961 Enrico Fermi Award, winner of the 1971 Nobel Prize for Physics, and previously a scientific adviser at the nuclear test-ban talks in Geneva – sent on April 25, 1997 to U.S. President Bill CLINTON; see Federation of American Scientists (FAS), <http://www.fas.org/bethepr.htm>. • President CLINTON, answering BETHE’s letter on June 2, 1997, diplomatically pointed out that he had directed “that the United States maintain the basic capability to resume nuclear test activities prohibited by the Comprehensive Test Ban Treaty in the unlikely event that the United States should need to withdraw from this treaty.”

biological, medical, political and logistical viewpoints.³³⁷ It is a tale that is both fascinating and repulsive: on the one hand, it was an incredibly challenging task that involved physicists, chemists, engineers and technicians exploring a completely new area of research, and the pressures of war demanded that their work had to be both swift and successful. On the other hand, the nuclear weapons that resulted from the work provided their possessors with massive potential for destruction and terror, which could threaten even the existence of life on Earth. Furthermore, the progress made in nuclear weaponry, together with the significant advances obtained in supersonic and hypersonic aerodynamics, rocketry and digital computers since the 1940s, completely changed the international political scene, military strategies, the global economy, and even our own personal lives, right up to the present day. All of these dramatic changes created a new world of previously unknown threats and anxieties.

³³⁷ The classic of this genre, which describes American efforts, is the book by Richard RHODES, *The Making of the Atomic Bomb* [Simon & Schuster, New York, 1986]. The book by Lillian HODDESON ET AL.: *Critical Assembly. A Technical History of Los Alamos during the Oppenheimer Years, 1943–1945* [Cambridge University Press, Cambridge, 1993], treats in detail (i) the research and development that led to implosion and gun weapons; (ii) the chemistry and metallurgy that enabled scientists to design these weapons; and (iii) the conception of the thermonuclear bomb, the so-called “Super.” An excellent survey of U.S. nuclear weapons development, covering the pioneering period 1939–1963 and including many unique illustrations, is given by Frank H. SHELTON in his book *Reflections of a Nuclear Weapons Engineer* [Shelton Enterprise, Inc., Colorado Springs, CO, 1988]. The Los Alamos Museum edited the informative brochure *Los Alamos 1943–1945; The Beginning of an Era* [Rept. LASL-79-78, July 1986]. The more recent book *Picturing the Bomb* [Abrams, New York, 1995] by Rachel FERMI (granddaughter of Enrico FERMI) and Ester SAMRA contains a unique gallery of photographs from the secret world of the Manhattan Project.

Similar activities in this field that were carried out in the Soviet Union during the period 1939–1956 are comprehensively described in David HOLLOWAY’s book *STALIN and the Bomb* [Yale University Press, New Haven, CT & London, 1994]. In addition, several renowned Soviet pioneers of shock wave and detonation physics have more recently given most interesting accounts of their roles and tasks in the development of nuclear weapons, such as Lev. V. AL’TSHULER, Yulii B. KHARITON, Igor V. KURCHATOV, Andrei D. SAKHAROV, and Yakov B. ZEL’DOVICH. Models of the first American and Soviet atomic bombs are shown in the Bradbury Science Museum at Los Alamos, New Mexico, and in the Museum of Nuclear Weapons at Arzamas-16, Sarov, Russia, respectively.

Nuclear research carried out in Germany during World War II was not directed towards building atomic bombs; see H.A. BETHE: *The German uranium project*. *Phys. Today* **53**, 34–36 (July 2000). However, speculations by numerous German scientists who fled Nazi Germany in the 1930s stimulated the governments of the United States and Great Britain to begin their own efforts in order to anticipate possible German atomic weaponry. Recent investigations carried out by some German science journalists have brought to light the fact that a few scientists tried to develop a simple fusion bomb in Germany during World War II [HAJEK \Rightarrow 1955]. However, these scientists were not seriously supported by the German Ministry of War.

The development of nuclear weapons encompassed unprecedented and complex shock- and detonation-related problems that required comprehensive theoretical and experimental studies for their solutions. When the Manhattan Project was set up in June 1942, considerable research into fission had already been performed in previous years, particularly in some European countries. There was also a solid foundation of basic knowledge of shock wave and detonation physics, although this was only understood and applied by a minority of scientists and engineers. European aerodynamicists and ballisticians had also developed a basic understanding of high-speed diagnostics and microsecond high-speed photography, but the application of their methods as well as the duplication of their apparatus was an art rather than a consolidated technique that was commercially available. The challenging goal of building an atomic bomb within the short period of three years only became possible because a significant number of top scientists from American universities were hired and incorporated into the Manhattan Project. In addition, a considerable number of renowned scientists from Europe, many of whom had escaped Nazi Germany in the 1930s and emigrated to the United States or England, brought their competence in nuclear physics, fluid dynamics, chemistry, metallurgy and high-speed diagnostics to the project. Their substantial knowledge could be rapidly focused on the problems involved and effectively exchanged between the Allied research institutions.

Milestones in Nuclear Physics. Numerous important discoveries, technological achievements and speculations were used by early nuclear weapons engineers to develop a nuclear bomb small enough to be dropped from an aircraft. These main milestones include:

- ▶ the discovery of radioactivity (A.H. BECQUEREL 1896);
- ▶ the first concept of an “atomic bomb,” which originated in science fiction {WELLS \Rightarrow 1914} but was first patented by L. SZILARD in 1934;
- ▶ the invention of the cyclotron (E. LAWRENCE 1930);
- ▶ the discovery of the hydrogen isotope “deuterium” (H.C. UREY 1931);
- ▶ the discoveries of the “neutron” {CHADWICK \Rightarrow 1932} and the “positron” (C.D. ANDERSON 1932);
- ▶ the splitting of the lithium nucleus into two alpha particles (J.D. COCKROFT & E.T.S. WALTON 1932);
- ▶ the discovery of the uranium isotope U-235 {DEMPSTER \Rightarrow 1935};
- ▶ the first demonstration of nuclear “fission” in uranium {HAHN & STRASSMANN \Rightarrow 1938; FRISCH & MEITNER \Rightarrow 1939};

- ▶ the recognition of the enormous energy released in fission processes in Germany {HAHN & STRASSMANN \Rightarrow 1938; S. FLÜGGE 1939; HEISENBERG \Rightarrow 1939}, Denmark {FRISCH & MEITNER \Rightarrow 1939; N. BOHR 1939}, and the Soviet Union (Y.B. ZEL'DOVICH & Y.B. KHARITON 1939);
- ▶ the assumption (based on theoretical analysis) that the component most likely to undergo fission when bombarded with neutrons, thus yielding more neutrons in sufficient numbers to possibly sustain an explosive chain reaction, was not U-238 but instead the rather less common isotope U-235 (N. BOHR & J.A. WHEELER 1939); the first experimental evidence of such a “chain reaction” was provided by I. JOLIOT-CURIE in 1939;
- ▶ the initiation of the American program to build an atomic bomb by the Einstein-Szilard letter addressed to the U.S. President Theodore ROOSEVELT {A. EINSTEIN \Rightarrow 1939};
- ▶ the discovery of spontaneous fission in uranium – *i.e.*, fission that occurs without the need for neutron bombardment (K.A. PETRZHAK & G.N. FLEROV 1940);
- ▶ the successful isotope separation of natural uranium by gaseous diffusion (O.R. FRISCH & R.E. PEIERLS 1940; J.R. DUNNING & E.T. BOOTH 1941);
- ▶ the (secret) discovery of plutonium Pu-239, the first transuranic element {SEABORG, KENNEDY, WAHL & SEGRÉ \Rightarrow 1941}; and
- ▶ the first evidence of a self-sustaining chain reaction in an uranium “reactor” (E. FERMI 1942).

The First Types of Nuclear Bombs. Nuclear weaponeers elaborated on two bomb concepts:

- ▶ the *gun-assembly device* proposed by Los Alamos scientists in the early 1940s and, independently, by Soviet scientists (Y.B. KHARITON, Y.B. ZEL'DOVICH & G.N. FLEROV 1941); and
- ▶ the *implosion-assembly device* proposed by U.S. scientists (J. VON NEUMANN & S. NEDDERMEYER 1943).

The applicability and effects of nuclear weapons based upon fission were demonstrated impressively by the successful test of the first fission bomb {Trinity Test \Rightarrow 1945}, and its first use for military purposes {Hiroshima & Nagasaki Bombing \Rightarrow 1945}. However, at the end of World War II the idea of a weapon based upon fusion, a so-called “thermonuclear bomb” or “H-bomb,” was still the subject of much discussion {FERMI & TELLER \Rightarrow 1941}. Edward TELLER’s “Super,” which used liquid deuterium as a fuel kept at about -250°C ,

was successfully tested in 1952 {MIKE Test \Rightarrow 1952}. In the former Soviet Union, the first successful thermonuclear test was performed only a few months after the American MIKE test {Semipalatinsk \Rightarrow 1953}. However, the Soviet device was a more advanced design and had already been constructed as a compact, aircraft-deliverable weapon.

Compared to fission bombs, once the explosion is started (by a fission bomb) in a fusion bomb, the production of additional explosive energy is relatively inexpensive. Therefore, large-yield bombs are most efficiently based upon fusion. The shock and heat effects of a fusion bomb are similar to the effects of fission bombs, although they are usually more powerful and, therefore, all effects must be scaled up.

Although over 50 years have passed since the MIKE Test and a number of other countries have developed fusion bombs since then, the construction details for TELLER’s Super are still secret. TELLER,³³⁸ who is generally considered to be the father of the hydrogen bomb, wrote an encyclopedia article in 1974 on this subject, concluding that: “The development of the technical ideas that led to the first man-made thermonuclear explosion is secret, as is the history of construction of the hydrogen bomb itself ... After the American and Russian tests, thermonuclear explosions were produced by the British (1957), the Chinese (1967), and the French (1968). It became evident that secrecy does not prevent the proliferation of thermonuclear weapons. It is doubtful whether an international nonproliferation treaty will be effective. Since secret tests of thermonuclear bombs are not easy, such a treaty has a somewhat better chance to limit the capability for hydrogen bomb warfare.” TELLER only gave a very general schematic of the operation of a fusion bomb. However, in the following edition of *The Encyclopedia Americana*, Mark CARSON,³³⁹ a competent Manhattan Project scientist who led the team of physicists that developed the hydrogen bomb at Los Alamos, became more specific in his article *Atomic Bomb*, in which he also provided a more detailed schematic on the design of nuclear weapons, including the hydrogen bomb.

U.S. Plowshare Program. Compared to the use of nuclear explosions for military applications, attempts to use them for peaceful purposes have only been partially successful. The Plowshare Program { \Rightarrow 1958} was established in 1958 by the U.S. Atomic Energy Commission (AEC) – now the Dept. of

³³⁸ E. TELLER: *Hydrogen bomb*. In: *The Encyclopedia Americana*. Americana Corp., New York, vol. 14 (1974), pp. 654-656.

³³⁹ M. CARSON. *Atomic bomb*. In: *The Encyclopedia Americana*. Americana Corp., New York, vol. 2 (1997), pp. 641-642.

Energy (DOE) – in order to explore the technical and economic feasibility of using nuclear explosives for industrial applications, such as for excavation {Test SEDAN \Rightarrow 1962, \Rightarrow Fig. 4.16–J; Test BUGGY \Rightarrow 1968, \Rightarrow Fig. 4.16–K}: including the creation of canals and harbors, the carving of highways and railroads through mountains, open pit mining, dam construction, and quarry projects. In addition, underground nuclear explosions were believed to be applicable for stimulating natural gas production {Test GASBUGGY \Rightarrow 1967}, the creation of underground natural gas and petroleum storage reservoirs, *etc.* The most spectacular project proposed was certainly the construction of a larger Panama Canal {Atlantic-Pacific Interoceanic Canal Study Commission \Rightarrow 1970} using nuclear explosions. The Plowshare Program comprised 27 Plowshare nuclear tests with a total of 35 individual detonations. It was discontinued in 1975.

Nuclear explosions were also used for some scientific purposes. Examples given in the CHRONOLOGY include:

- ▶ the generation of an artificial radiation belt to test the confinement of charged particles in magnetic fields on a very large scale {Project STARFISH \Rightarrow 1962}; and
- ▶ the generation of ultrahigh shock pressures using nuclear explosions {RAGAN ET AL. \Rightarrow 1977; TRUNIN ET AL. \Rightarrow 1992; \Rightarrow Fig. 4.11–F}.

Soviet Plowshare Program. The Soviet program “Nuclear Explosions for the National Economy” was the equivalent of the U.S. program Operation Plowshare { \Rightarrow 1958}. The best known of these nuclear tests in the West was the Chagan Test {1965} as radioactivity from this underground test was detected over Japan by both the U.S.A and Japan in apparent violation of the 1963 Limited Test Ban Treaty {Nuclear Test Ban Treaty \Rightarrow 1963}.

New Generations of Nuclear Weapons. Today’s thermonuclear weapons consist of two separate stages. The first stage is a nuclear fission weapon that acts as a trigger for the second stage. The explosion of the fission trigger produces a temperature and pressure that is high enough to fuse together the hydrogen nuclei contained in the second stage. The energy from this nuclear fusion produces a large explosion and a large amount of radioactivity.

Tomorrow’s thermonuclear weapons will probably not rely on a nuclear-fission trigger to provide the conditions needed for nuclear fusion. Instead, they may use new types of very powerful but conventional high explosives, arranged, for example, in a spherical shell around a capsule containing

the hydrogen gases tritium and deuterium. When the explosives are detonated, the capsule will be crushed inwards and the gases rapidly heated to a temperature high enough to allow the fusion of hydrogen nuclei to take place. Such a pure nuclear fusion weapon based upon inertial confinement would be relatively simple to design and construct. Since no fissible materials are required, this would be the ideal terrorist weapon for the 21st century. In order to achieve levels of nuclear fusion that are militarily useful, new explosives are being developed that can produce energy concentrations that are much greater than those produced by today’s conventional high explosives.³⁴⁰

Similar concepts, combined with a hollow-charge compression technique, were already envisaged during World War II in the United States (J. VON NEUMANN 1943) and studied in Germany (later continued in France) {HAJEK \Rightarrow 1955}, but obviously without succeeding in initiating by this simple way a fusion reaction.

‘Dirty Bomb’ Explosion. Over the past few years a new type of nuclear explosion has been discussed in the press: so-called “dirty nuclear explosions.” A “dirty bomb”³⁴¹ has been defined by the U.S. Department of Defense (DOD) as a “Radiological Dispersal Device” (RDD). The bomb produces a conventional chemical explosion, but it contains radioactive material, and so it is used to spread radiation over a wide area. Although a dirty bomb is not a true nuclear bomb and does not produce the heavy damage of a nuclear blast, it could have a significant psychological impact when applied in a city, causing fear, panic and disruption, and forcing costly cleanup operations.³⁴² In addition, exposure to radioactive contamination could increase the long-term risk of cancer. Such a bomb could therefore provide a simple but effective weapon for terrorist warfare when used in cities and other densely populated areas.

³⁴⁰ From a lecture Frank BARNABY presented at the 13th World Congress of International Physicians for the Prevention of Nuclear War (IPPNW), held at Melbourne, Australia, in 1998. BARNABY, a British nuclear physicist who worked at the Atomic Weapons Research Establishment (AWRE), Aldermaston and was director of the Stockholm International Peace Research Institute (SIPRI), wrote the book *How to Build a Nuclear Bomb: and Other Weapons of Mass Destruction* [Granta, London, 2003].

³⁴¹ The term *dirty bomb* was coined by the media to describe a radiological dispersion device that combines conventional explosives, such as dynamite, with radioactive materials in the form of powder or tiny pellets packed around the explosive material. The effects of such a bomb are limited to the conventional blast damage at the site of the explosion and the contamination from radioactive materials spread by the blast (from WHO/RAD Information Sheet, Feb. 2003).

³⁴² M.A. LEVI and H.C. KELLY: *Weapons of new mass destruction*. *Scient. Am.* **287**, 58–63 (Nov. 2002).

2.7 EVOLUTION OF SEISMOLOGY

*Now the recent improvements in the art of exploding, at a given instant, large masses of gunpowder, give us the power of producing an artificial earthquake at pleasure; we can command with facility a sufficient impulse to set in motion an earth wave that shall be rendered evident by suitable instruments at the distance.*³⁴³

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Dublin 1846

SEISMOLOGY – now widely recognized as being the Earth science that is concerned with the scientific study of natural and man-made earthquakes, and the movement of waves through the Earth – has its roots in percussion rather than in classical shock wave physics. The term *seismology*, derived from the Greek word *seismos*, meaning “earthquake,” was coined by Robert MALLET {⇒1857}, an Irish engineer and a cofounder of seismology. Originally, one of the main aims of investigations in this field was to study the seismic (elastic) waves generated by an earthquake, a complex mixture of various types of body waves and surface waves. These “seismic shocks” are not shock waves in the conventional sense; *i.e.*, they do not show the typical steep shock front, the high pressure, or the extremely short shock durations (on the order of micro- or even nanoseconds) of shock waves.

Classical seismology primarily involves the study of earthquakes as a geophysical phenomenon and the study of the internal structure of the Earth; important practical applications include seismic prospecting {⇒Fig. 4.15–E} and the seismic monitoring of nuclear explosions {⇒Fig. 4.3–Z}.³⁴⁴ However, more recently, the field of seismology has expanded to encompass the study of elastic waves in other celestial bodies too.

- ▶ The first extraterrestrial *passive seismic experiments* were carried out on the Moon during the four Apollo (12/14/15/16) missions, and they have also been performed on Mars {Viking 2 Mission ⇒1975}.
- ▶ *Active seismic experiments* were among the first to be deployed on the Moon. During the Apollo 14/16/17 missions, active seismic experiments using explosives were conducted on the Moon to determine the structure of and the velocity of sound through its upper crust {Apollo 14 ⇒1971; Apollo 17 ⇒1972}.

- ▶ Asteroid seismology can help us to understand their internal structure and to get information on their material properties, which are currently unknown {NEAR ⇒1996}.
- ▶ Modern seismology has even been extended to the Sun, thus creating in the 1960s *helioseismology*, a branch of solar physics that investigates pressure wave oscillations in the Sun caused by processes in the larger convective region. Since the Sun’s “surface” is not directly accessible via landers, and so it is not possible to install seismometers on the Sun as done on the Moon, *helioseismology* makes use of astronomical (optical) observations of seismic oscillatory waves in order to determine the inner structure of the Sun.³⁴⁵ Acoustic, gravity and surface gravity waves generate different resonant modes in the Sun which appear as up and down oscillations of the gases: the oscillation modes are observed as Doppler shifts of spectrum lines and they can be used to sample different parts of the solar interior {WOLFF ⇒1972; KOSOVICHEV & ZHARKOVA ⇒1998; ⇒Fig. 4.1–V}.

The novel research domain of *asteroseismology* refers to studies of the internal structures of pulsating stars, which involve interpreting their frequency spectra. Asteroseismologists make great use of such oscillations to probe stellar interiors that are not observable directly. The basic principles of asteroseismology are very similar to those developed to study the seismology of the Earth.³⁴⁶

2.7.1 EXPLOSION SEISMOLOGY & VIBROSEIS

The new field of seismology was significantly boosted when it became possible to produce seismic shocks artificially by a concussive force, for example by using explosives {MALLET ⇒1846, 1849 & 1860; ABBOTH ⇒1878; MILNE & GRAY ⇒1883; DUCAN ⇒1927}. Use of the explosion method, which is the oldest one, created the new discipline of *explosion seismology*, which is of great economic and scientific value. Explosions are useful in this sense because the source mechanism is less complex than for most earthquakes, and the locations and detonation times are generally known precisely. Almost half of the seismic data collected on land have been acquired using explosive sources such as charges of dynamite. This enabled not only rapid testing and

³⁴³ R. MALLET: *On the dynamics of earthquakes*. Trans. Roy. Irish Acad. **21**, 50–106 (1846).

³⁴⁴ C. KISSLINGER: *Seismology*. In: (G.L. TRIGG, ed.) *Encyclopedia of applied physics*. VCH, New York *etc.*, vol. 17 (1996), pp. 155–174, and *Update 1* (1999), pp. 415–422.

³⁴⁵ D.O. GOUGH ET AL.: *Perspectives in helioseismology*. Science **272**, 1281–1283 (May 31, 1996).

³⁴⁶ *Asteroseismology*. Institute of Astronomy, Katholieke Universiteit, Leuven, Belgium; <http://www.ster.kuleuven.be/research/asteroseism/>.

improvements in seismic diagnostics, but it also stimulated subsurface exploration. In particular, the application of refraction and reflection techniques {KNOTT \Rightarrow 1899; MINTROP \Rightarrow 1919 & 1924; DUNCAN 1927; \Rightarrow Fig. 4.15–E} in conjunction with strong explosions has provided detailed knowledge of the structure of the Earth's crust and even of its inner core {GUTENBERG ET AL. \Rightarrow 1912}. Furthermore, evidence that earthquakes can be triggered by detonating chemical explosives or nuclear devices underground has enhanced man's understanding of earthquake mechanisms and has led to more accurate predictions of seismic shock arrival times.

Historically, explosion seismology started with black powder. However, since black powder cannot be detonated, the seismic shocks generated using it were not strong enough to be recorded at great distances, which was initially an important prerequisite for better resolving and differentiating between P- and S-waves using the seismographs available at that time. With the advent of high explosives, these seismic studies could be successfully extended to measure seismic velocities in all kinds of geological materials, and to investigate focal mechanisms and effects of large disturbances at greater depths.

Modern seismography allows one to differentiate between natural disturbances (e.g., earthquakes, volcanic eruptions, meteorite impacts) and those generated artificially by man (e.g., by large chemical or nuclear explosions), and to determine their locations and strengths. The discovery of the "boundary wave" [Germ. *Grenzwelle*] by the German geologist and seismologist Ludger MINTROP { \Rightarrow 1919}, a pseudo-supersonic wave phenomenon, allowed the depths and thicknesses of subterranean layers to be ascertained for the first time { \Rightarrow Fig. 4.15–E}. This so-called "Mintrop wave" [Germ. *MINTROPsche Welle*], which was initially kept secret because of its commercial applicability, was later rediscovered and visualized on a laboratory scale by the German physicist Oswald VON SCHMIDT { \Rightarrow 1938}. Among fluid dynamicists and acousticians, the Mintrop wave is better known as the "Schmidt head wave" [Germ. *VON SCHMIDT-sche Kopfwelle*] – also a pseudo-supersonic wave propagation phenomenon { \Rightarrow Fig. 4.14–O}, which allows one to optically determine the various wave speeds in optically transparent as well as opaque solid materials.

The expensive nature of the drilling required to deploy explosive sources can be circumvented by using nonexplosive sources: such approaches involve mechanically impacting the Earth's surface, achieved by applying a large dropping weight for example {MILNE 1880s; MINTROP \Rightarrow 1908}, or by shaking the surface with mechanical devices of various construction using vibrator trucks. Today, most onshore seismic data are acquired using the latter method, known as "Vibroseis®." This important seismic reflection method that was invented

and developed by John CRAWFORD, Bill DOTY, and Milford LEE at the Continental Oil Company (Conoco) in the early 1950s, imparts coded seismic energy into the ground. The energy is recorded with geophones and then processed using the known (coded) input signal. The resulting time-domain representation of vibroseis data is an impulsive wavetrain with wavelet properties consistent with the coded input signal convolved with the Earth's reflectivity series. Historically, vibratory seismic surveys collect data from one source location at a time, summing one or more sources at each location.

In *structural geology* – the branch of geology concerned with the deformation of rock bodies and with interpreting the natural forces that caused the deformations – artificial seismic waves became an important tool for the discovery of undersea mountain ranges with central rifts and massive transform faults. They are also applied to determine large-scale structures, for example to map sea floor stratigraphy and sedimentary structures. Geophones laid out in lines measure how long it takes the waves to leave the seismic source, reflect off a rock boundary, and return to the geophone. The resulting two-dimensional image, which is called a "seismic line," is essentially a cross-sectional view of the Earth oriented parallel to the line of geophones. Seismology, which was originally developed by the oil industry to perform seismic surveys, also became an important tool for the discovery of undersea mountain ranges with central rifts and massive transform faults.

2.7.2 SEISMOSCOPES, SEISMOGRAPHS, AND SEISMOMETERS

Proper measurement techniques were critical to progress in seismology, and the pioneers of seismology contributed considerably to the development of new diagnostic methods and instrumentation.

Early *seismoscopes* were rather crude instruments and were only capable of detecting the occurrence of earthquakes; some constructions were also capable of detecting the azimuths of their origin from the observer's location. The oldest known construction dates back to about A.D. 130 and was built in China { \Rightarrow Fig. 4.3–L}. *Seismometers* are sensors that quantitatively detect ground motions. Early seismometers were pendulums that were not, however, capable of recording high-frequency ground shaking. Modern seismometers produce an electric signal that can be recorded. At the beginning of the 20th century, electrodynamic systems were introduced that indicated ground velocity instead of displacement. In the early 1980s, force-balanced systems became available, which cover a high dynamic range (> 140 dB).

Great advances in seismology were achieved in the late 19th century with the invention of *seismographs*, which provided the first records (*seismograms*) of ground motion as a continuous function of time. Seismographs are ingenious instruments for measuring and recording seismic shock waves; their contribution to geophysical and geological knowledge is comparable to the contribution of the telescope to astronomy, or high-speed photography to shock wave physics. In contrast to modern shock pressure gauges such as those used in modern solid-state shock wave physics, which have rise times on the order of nanoseconds, seismographs occupy the very low frequency regime (down to 10^{-4} Hz), and are capable of recording ground motions in three directions over a large dynamic range. Examples of famous seismograph constructions include:

- ▶ the *Palmieri seismograph* (1856), which is thought to have been the first to record the times of seismic shocks. The more advanced *electromagnetic Palmieri seismograph* (1877) served as an effective detector on Mt. Vesuvius in Italy for many years;
- ▶ the rolling-sphere *Gray seismograph* (1881), which was the first to allow ground tremors in any horizontal direction to be recorded {⇒ Fig. 4.3–M};
- ▶ the pendulum-based *Ewing seismograph* (1883), which was the first seismograph to be installed in the United States; it recorded the Great San Francisco Earthquake in 1906 {⇒ Figs. 4.1–E & 4.3–M}; and
- ▶ the photographically recording *Wiechert seismograph* {WIECHERT ⇒ 1898}, which used a viscously-damped pendulum as a sensor to lessen the effects of pendulum eigen-oscillations.

Generally, seismographic records can detect four separate groups of waves.³⁴⁷

- ▶ *compressional waves* or *longitudinal waves*, also known as “P-waves” (or “primary waves”), which have the highest propagation velocities of all seismic waves, ranging from 1.5 to 8 km/s in the Earth’s crust;
- ▶ *shear waves*, also known as “S-waves” (or “secondary waves”), which involve mainly transverse motion, usually at 60–70% of the speed of P-waves. S-waves are felt in an earthquake as the “second” wave, they do not travel through liquids;
- ▶ *Rayleigh surface waves* {Lord RAYLEIGH ⇒ 1885} have a rotating, up-and-down motion like that of breakers at sea. They have the smallest propagation velocities, but often exhibit much larger amplitudes than the other waves, and are then very destructive.

Most of the shaking felt during an earthquake is due to Rayleigh waves; and

- ▶ *Love surface waves*, the fastest type of surface wave, discovered by the British geophysicist August E.H. LOVE (1911). These move transversely, whipping back and forth horizontally without agitating the surface vertically or longitudinally.

It is possible to determine the distance and origin of an earthquake from the arrival times of the different waves. However, the complex nature of seismic waves made it very difficult for early earthquake researchers to correctly read and interpret seismograms. Just to add to their troubles, these seismograms were also obtained by crude and imperfect instrumentation with low temporal resolution, low sensitivity, and a small dynamic range. Today sophisticated short-, intermediate-, and/or long-period multi-component seismometers are operated in networks, and the seismic data, which is continuously digitally recorded at many locations around the world, are exchanged among seismic observatories via the Internet or other interconnected computer networks and they are analyzed using sophisticated computer programs.

2.7.3 SEISMIC PROSPECTING AND RESEARCH

The most valuable economic spin-off resulting from seismology was *seismic prospecting*. Initially this method of exploration used chemical explosives to induce a percussion force in the ground {MALLET ⇒ 1849 & 1860; ABBOT ⇒ 1876}, but other artificial sources were subsequently developed, such as heavy-duty thumper trucks (*vibroiseis*), which create vibrations by hammering the ground. These trucks produce a repeatable and reliable range of frequencies, and are a preferred source of vibrations compared to dynamite. In offshore locations, specially designed vessels are deployed. They are equipped with arrays of air guns which shoot out highly pressurized air into the water, creating a concussion that hits and vibrates the sea floor. Shock guns {Europe ⇒ 1957} have also been used for marine prospecting.

During the 1920s and 1930s, two seismic techniques – the *reflection method* and the *refraction method* {⇒ Fig. 4.15–E} – were developed and immediately applied for prospecting purposes in the oil-producing regions of the United States {MINTROP ⇒ 1919; Orchard Dome ⇒ 1924} and Mexico. The U.S. general scientist Dr. Thomas POULTER,³⁴⁸ who participated in Admiral Richard BYRD’s Antarctic expedition to the South Pole (1933–1935), was the first to measure the ice

³⁴⁷ Illustrious schematics of the wave motion of these four wave types were given by Bryce WALKER in his book *Earthquake*. Time-Life Books, Alexandria, VA (1982), p. 79.

³⁴⁸ T. POULTER: *Seismic measurements on the Ross Shelf Ice*. Trans. Am. Geogr. Union **28**, 162–170, 367–384 (1947).

thickness and the contour of the bottom of the Ross Shelf using seismology. Today seismology plays an important role in both land and marine seismic surveys.

The two different and competing methods are based on the reflection or refraction of seismic waves and their proper detection by seismographs. Initiated by some compressive force, these seismic or elastic earth waves travel down to a dense or high-velocity bed; they are then carried along that bed until they are re-refracted or reflected upwards, respectively, to seismic detectors located on the surface some distance from the shot point. It is the time required for the seismic wave to reach each detector from the shot point that is recorded. The speed of transmission of the waves through different geological structures is proportional to the density or the compactness of the formation. Unconsolidated formations such as sands transmit waves at a low velocity, and massive crystalline rocks such as rock salt allow high propagation speeds. Generally, the density of the rock near the surface of the Earth increases with depth. When a seismic wave is refracted at the boundary of a deeper layer, the pulse travels at the velocity of sound in the lower layer, *i.e.*, supersonically with respect to the velocity of sound in the upper layer {⇒Fig. 4.15–E}. The wave propagation is therefore analogous to the Schmidt head wave {⇒Fig. 4.14–O}. During its propagation in the boundary layer it sends secondary waves into the upper medium, which arrive at the surface where they are recorded as function of time in a seismogram. On the other hand, seismic waves reflected at the boundary of two layers return immediately to the surface. However, the refracted wave arrives prior to the reflected wave at greater distances between the shot point and the receiving station.

Seismic surveying proved very useful, not only when exploring for oil and gas, coal, minerals and groundwater, but also in other fields. In geophysical research, the achievement of more accurate mapping is of broad interest in scientific studies of the Earth and of earthquake physics. For example, the systematic use of seismographs on an international scale allowed the exchange of global seismic data, which enormously enhanced not only our understanding of earthquakes, but also our knowledge of the Earth's interior. The German geophysicist Beno GUTENBERG {⇒1912} from Göttingen University made the first correct determination of the radius of the Earth's fluid core while carefully analyzing seismic data from a remote earthquake. In 1936, the Danish seismologist Inge LEHMANN interpreted waves in the shadow zone as P-waves that were reflected on a 5,000-km-deep discontinuity, thus indicating a region with different properties inside the fluid core. The solidity of this inner core was first suggested in the 1940s by the Australian

geophysicist and mathematician Keith Edward BULLEN, and it was proven in 1971 by the Polish-born U.S. geophysicist Adam M. DZIEWONSKI and the U.S. earth scientist Freeman GILBERT using observations of the Earth's free oscillations.

High-resolution marine seismic techniques are currently being applied at the University of Southampton to archaeological remains and for mapping purposes, and the theoretical and practical advantages of this technique are being investigated for geophysical surveys of wooden artifacts and shallow intertidal sites.

Seismic event detection and location are also considered to be the single most important research issues involved in monitoring the Comprehensive Test-Ban Treaty {CTBT ⇒1996}. However, nuclear explosion and nonproliferation monitoring {⇒Fig. 4.3–Z} requires the processing of huge amounts of seismic sensor data – a difficult and challenging task which can only be achieved by using complex automated algorithms to characterize seismic events.

2.8 HIGH-SPEED DIAGNOSTICS

Today's science strives to create its world view based not on speculations but – if possible – rather on observable facts: now it examines its constructions by observation. Each newly observed fact supplements the world view, and each deviation of a construction from the observation draws attention to an imperfection, a gap. The visualized is examined and supplemented by the imagined, which itself is the result of the previously visualized. Therefore, there is a special charm to verifying things by observation – i.e., by perceptions that have only been theoretically developed or assumed.³⁴⁹

Ernst MACH
Universität Wien
Vienna 1897

WHEN the English monk, philosopher and statesman Sir Francis BACON suggested his experimental methodology, which involved taking things to pieces [Lat. *dissecare naturam*], it led to a preferred way of dividing the world into object and observing systems. In particular, it stimulated the evolution of classical mechanics tremendously. The application of this methodology led to the dissection of complex mechanical systems into their components in order to calculate the forces and momentums involved in the systems. This method was rendered most useful with the advent of Sir Isaac NEWTON's three Laws of Motion. In addition, the dissection of time, the "fourth dimension," also proved to be most useful. The analysis of

³⁴⁹ E. MACH: *Populär-wissenschaftliche Vorlesungen*. Barth, Leipzig (1903), pp. 351–352.

physical and chemical processes performed by splitting them into a series of single time steps, one following the other, was one of the most successful ideas in the evolution of science and technology – and it still is today. High-speed cinematography is the most effective technique to use to reach this goal, and it is the ideal way to understand the nature of rapid events that are otherwise inaccessible to the naked eye. In particular, military research has prompted much development in high-speed diagnostics.

The basic questions that are usually asked in the study of any high-speed event are (i) how rapid is it and (ii) how long does it go on for. A classic example is the temporal measurement of pressure in a gun barrel. This was not only of vital interest to early ballisticians attempting to improve firearms, but such an analysis was also crucial to obtaining a basic understanding of wave propagation in gaseous matter, and it is no accident that fast chronoscopes originated in this area of research. Another important condition is triggering – *i.e.*, the appropriate timing of the diagnostics in order to catch the high-speed event within the selected time window of recording. Since supersonic phenomena cannot be resolved with the naked eye, *high-speed visualization* is an indispensable tool for shock wave and detonation research, which therefore relies on three essential “ingredients:”

- ▶ an appropriate optical method of visualization;
- ▶ a method of recording the data for later temporal and spatial analysis; and
- ▶ a reliable method of triggering.

These three basic conditions will be discussed in the following paragraphs.

2.8.1 PRECISE TIME MEASUREMENT: THE CRUCIAL CONDITION

*It was my intention to visualize the compression wave which, carrying the sound originating from an electric spark, spreads into the atmosphere in all directions. Eventually I let the sound-producing spark discharge closely in front of the schlieren head and – very shortly thereafter – there was a second spark at the position of the illuminator, illuminating the field of view over a very short time interval so that the sound wave should still be visible in the field of view.*³⁵⁰

August TOEPLER
Königl. Landwirthschaftliche Akademie
Poppelsdorf/Bonn 1864

The ambitious development of precision measurement devices that took place in the 19th century was almost entirely

due to the requirements of basic ballistics. For example, in interior ballistics the measurement of the actual position of the projectile in the barrel is an important condition for calculating its acceleration, and for estimating the burning behavior and efficiency of a new propellant. In exterior ballistics, measurements of the time of flight allowed the velocity of the projectile as it left the muzzle (the so-called “muzzle velocity v_0 ”) and the decrease in the projectile velocity along its trajectory to be studied.³⁵¹ These studies provided a deeper look into various fundamental problems related to aerodynamic drag at supersonic velocities, and they were first performed by Benjamin ROBINS {⇒1746} for musket shot and by Charles HUTTON {⇒1783} for cannon shot. In addition, the mass production of firearms required reliable testing and quality control, which also included the determination of v_0 . However, the application of the classical ballistic pendulum {CASSINI JR. ⇒1707; ROBINS ⇒1740 & 1746} made such measurements rather cumbersome, not very accurate and difficult to apply to large caliber guns.

Chronoscopes and Chronographs. The evolution of fast chronoscopes – instruments for precisely measuring the duration of a single high-speed event or of several events, and their temporal correlation – began in Germany (Preußische Artillerie-Prüfungskommission 1838) and England {WHEATSTONE ⇒1839; ⇒Fig. 4.19–A} with the incorporation of an electromagnetic trigger into a mechanical clock in order to start it and stop it. The so-called “Wheatstone chronoscope” allowed one to measure the time of flight of a projectile by positioning a breaking contact in front of the muzzle and a closing one at the target. In the early 1840s, the Wheatstone chronoscope was improved considerably by the German-born Swiss watchmaker Matthias HIPP. This “Hipp-Wheatstone clock” {⇒Fig. 4.19–A} was widely used in ballistics, astronomy and physiology.

Shortly after, special mechanical-electrical devices – *chronographs* – were devised for measuring, indicating and permanently recording the duration of an event. Prominent examples include a falling vertical pendulum invented in 1848 by Captain A.J.A. NAVEZ³⁵² of the Belgian Army, the “Navez chronograph” (1853), and a unique dropping-weight timing system constructed in the early 1860s by the Belgian military engineer Major Paul-Emile LE BOULENGÉ {⇒1860s & 1882}

³⁵¹ In order to characterize the drag of a projectile, 19th-century ballisticians also began to use quantities other than v_0 – for example v_{50} , the projectile velocity measured 50 meters away from the muzzle.

³⁵² A.J.A. NAVEZ: *Application de l'électricité à la mesure de la vitesse des projectiles*. J. Corréard, Paris (1853); *Instruction sur l'appareil électro-ballistique*. J. Corréard, Paris (1859).

³⁵⁰ See A. TOEPLER {⇒1864}, pp. 30–31.

of the Belgian Artillery. This “Le Boulengé chronograph” {⇒Fig. 4.19–B} recorded the time elapsed through knife marks made on the surface of a falling cylindrical rod. This instrument was used for around a hundred years, and proved to be versatile and surprisingly accurate. It was widely used to measure the flight times in open ballistic ranges as well as the detonation velocities of explosive gaseous mixtures in a laboratory environment {BERTHELOT & VIEILLE ⇒1882}.

The idea of electrical triggering – a high-tech revolution of tremendous potential at that time – resulted in a variety of other self-recording instruments which used electrical-mechanical and photographic methods of recording. For example, in the 1840s Werner VON SIEMENS,³⁵³ then a Prussian artillery officer and not yet ennobled, constructed an electroballistic chronograph, the “Siemens chronograph.” Using a spark gap as the writing element, it consisted of a fixed needle electrode and a polished steel surface of a rotating drum, which was used as the counter-electrode. At the moment of departure from the muzzle, the projectile prompted the discharge of a Leiden jar across this needle-drum gap via a two-wire-gauge positioned at the muzzle of the test gun, which generated a small, sharply defined mark on the drum surface. After a specified flight distance, a second Leiden-jar circuit was discharged via a second two-wire-gauge with a second needle electrode in series, thus creating a second mark on the rotating drum. The elapsed time was determined as the distance between the two spark marks on the drum.

The enormous progress made at this initial stage of electrical chronometry also benefited other branches of science; for example it was used in astronomy to determine the longitudes and culminations of stars with greater precision. Starting in the 1870s, the development of short-timescale chronometry in England, France and Germany was pushed forward by the rapidly increasing number of new ballistic propellants and high explosives, as well their increased use in civil and military applications. In addition, the increasing pressure that was placed on the mining industry to prevent firedamp explosions required more precise research instruments in order to better resolve the nature of these rapid explosion processes.

In the early 1860s, the Rev. Francis A. BASHFORTH, a British professor of mathematics at Woolwich, devised an electric chronograph that measured down to fractions of a second by interpolation. This “Bashforth chronograph” was used by him to measure aerodynamic drag in the supersonic range {BASHFORTH ⇒1864}. In his instrument, a platform was arranged to descend slowly alongside a vertical rotating

cylinder. The platform carried two markers controlled by electromagnets, which produced a double spiral on the surface of the cylinder. One electromagnet was linked by a circuit to a clock, and the marker actuated by it marked seconds on the cylinder. The circuit of the other electromagnet was completed through a series of contact pieces attached to the screens through which the shot passed in succession. When the shot reached the first screen, it broke a weighted cotton thread which kept a flexible wire in contact with a conductor. When the thread was broken by the shot, the wire left the conductor and almost immediately established the circuit through the next screen by engaging with a second contact. The time of the occurrence of the rupture was recorded on the cylinder by the second marker.³⁵⁴

The British ballistician Sir Andrew NOBLE {⇒1873} constructed a chronograph that used spark traces generated by inductance coils, which were recorded on a rotating drum covered with paper: the “Noble chronograph” {⇒Fig. 4.17–L}. Later extended to a system of multiple-spark traces – the first multichannel chronograph – it was applied by NOBLE to interior ballistics in order to record the arrival times of a projectile at various points within a gun barrel. Each recording channel was provided with little wire gauges which protruded into the barrel and were connected in series with each inductance coil; these were cut upon the passage of the projectile, thus interrupting the flow of current in the inductance coil and stopping the spark trace. By graphically differentiating the distance-time profile obtained twice, NOBLE obtained the acceleration of a fired projectile and, using Sir NEWTON’s Second Law of Motion, the corresponding instantaneous force that acted on its base.

The French engineer Marcel DEPREZ constructed a chronograph similar to the Siemens chronograph. However, he used a soot layer on a revolving drum for recording purposes. Furthermore, unlike the Noble chronograph, he included an electrically activated tuning fork that produced a second trace for accurate time calibration purposes. Later DEPREZ improved his construction and extended it so that it could record 20 individual channels. The “Deprez chronograph” {DEPREZ ⇒1874} proved to be very useful for determining detonation velocities in gaseous mixtures {MALLARD & LE CHÂTELIER ⇒1881; BERTHELOT & VIEILLE ⇒1882}. In the years following, Hippolyte SÉBERT³⁵⁵ (1881), a French lieutenant colonel, improved the Deprez chronograph.

³⁵³ W. VON SIEMENS: *Über die Anwendung des elektrischen Funkens zu Geschwindigkeitsmessungen*. Ann. Phys. 66 [II], 435–444 (1845).

³⁵⁴ *The Encyclopaedia Britannica*. Cambridge University Press, Cambridge, vol. 6 (1911), p. 305.

³⁵⁵ H. SEBERT: *Notice sur de nouveaux appareils balistiques employés par la service de l’artillerie de la marine*. L. Baudoin, Paris (1881).

SÉBERT's instrument – the “Sébert chronograph” – was capable of precisely measuring times to an accuracy of less than $1/50,000$ second (20 μ s). It was widely applied in ballistics and detonation studies as a *velocimeter*; for example, it was used to measure projectile motion inside gun barrels and in free flight, detonation velocities of high explosives, and recoil motions of guns.

The “electric-tram chronograph,” which was invented by Frederick J. JERVIS-SMITH { \Rightarrow 1889} at Oxford, greatly differed from all previous time-measuring instruments. It used a moving plate which was carried on wheels and ran on rails, on which traces were made by means of electromagnetic styli. Capable of recording a large number of events separated by small periods of time, it was used by him to measure the acceleration periods of explosions, the velocities of bullets, and it was also used in many physiological time measurements. His tram chronograph was commercialized by the Elliot Brothers, two London instrument-makers.

All of the chronoscopes and chronographs discussed above were constructions that used a combination of mechanical and electrical elements. However, it is interesting to note here that fully electrical time measurement devices were also devised during this same pioneering period. The French physicist Claude S.M. POUILLET { \Rightarrow 1844} invented his famous “ballistic galvanometer,” a chronoscope for measuring projectile velocities. The galvanometer was connected to a battery via two grids which were connected in series and were activated as switches by the flying projectile. The deflection of the galvanometer was proportional to the quantity of electricity in the short current pulses and, therefore, to the projectile velocity. In England, the engineer Robert SABINE { \Rightarrow 1876} invented another chronoscope that was based on discharging a capacitor for a short period of time. The time elapsed was determined by the decrease in the voltage at the capacitor. The “Sabine chronoscope” was used in exterior ballistics; in this case the projectile traveled through two contact grids which, acting as switches, briefly discharged the capacitor by a small amount over a resistor with a constant resistance.

In the early 1910s, Carl CRANZ and Karl BECKER, two eminent ballisticians at the Berlin Military Academy, invented an electric spark photochronograph, the “Cranz-Becker chronograph” { \Rightarrow Fig. 4.19–J}, which they used in high-precision aerodynamic drag studies. During the following decades, many more constructions and derivatives of these classical instruments were invented to serve the needs of laboratory physicists and testing ground technicians who required them due to the fast progress being made in high explosives, shock waves and ballistics. A detailed review of

early chronoscope and chronograph developments was given in the 1910 *Encyclopaedia Britannica*³⁵⁶ and in CRANZ's famous textbook on ballistics.³⁵⁷

Electronic Timing Devices. The first electronic device for measuring time spans based upon an electronic binary digital circuit was constructed by Charles E. WYNN-WILLIAMS, a British physics professor at Cambridge University (1931). It employed thyratron tubes and was used to count radioactive rays registered by a Geiger counter. This electronic counter became increasingly popular before World War II. Since it was the first practical digital electronic counting device, it played a crucial role in the development of nuclear physics and paved the way to digital electronic computers. Based upon the *multivibrator* or *flip-flop*, which was also an English invention {ECCLES & JORDAN \Rightarrow 1919}, it had the great advantage that the elapsed time – which was later preselectable in units of micro- and even nanoseconds – could be read directly from the face of the instrument, which considerably facilitated the measurement of shock front velocities and improved its accuracy.

The first real electronic *oscillographs* were built prior to electronic counter development. They were based upon the cathode ray tube (c.r.t.), a significant instrument invented in 1897 by the German physicist Ferdinand BRAUN. Oscillographs are electronic instruments that (similar to chronographs) measure, indicate and permanently record quantities that vary of time using a c.r.t. or another electronic display. While early *oscilloscopes* also used a c.r.t., they were only capable of displaying fluctuating electrical signals on a fluorescent screen and, like chronoscopes, they could not record the signal permanently.

Unlike all mechanical chronographs, cathode-ray oscillographs are equally sensitive at all frequencies, from zero to the highest frequency of oscillation, and are therefore perfectly suited to recording impulsive or “transient” phenomena. However, these unique instruments were not initially available commercially, and shock and explosion pioneers had to build their own rudimentary oscillographs. Various recording methods were applied during this exciting pioneering period of cathode-ray oscillograph development.

The *Dufour-type oscillograph*,³⁵⁸ developed in France by Alexandre E. DUFOUR during and after World War I, was the

³⁵⁶ *The Encyclopaedia Britannica*. University Press, Cambridge, vol. VI (1910), pp. 301-305.

³⁵⁷ C. CRANZ: *Lehrbuch der Ballistik*. Springer, Berlin, vol. III (1927) *Experimentelle Ballistik*, pp. 35-133.

³⁵⁸ A.E. DUFOUR: *Oscillographe cathodique pour l'étude des basses, moyennes & hautes fréquences*. *L'onde électrique* 1, 638-663, 699-715 (1922); *Ibid.* 2, 19-42 (1923).

most advanced instrument of the time for recording impulsive phenomena electronically. It used a classical high-voltage (60-kV) Braun tube with a cold cathode. The electrons, generated via field emission, were accelerated in a soft vacuum to a high velocity in order to achieve an intense photographic effect on film. The film plate was positioned in the vacuum chamber and it was directly exposed to the cathode ray. Time sweeping was achieved through the use of magnetic coils, and a maximum cathode-ray spot velocity of 4,000 km/s (4 mm/ns) was realized. However, because of the high velocity of the cathode ray, the input voltage sensitivity was quite low.

The *Wood-type oscillograph*, the archetype of modern oscillographs, was devised by Joseph J. THOMSON, a British professor who received the Nobel Prize for Physics in 1906 for his discovery of the electron in 1897. The oscillograph was constructed and tested by his countryman Albert B. WOOD {⇒1923}. In contrast to the Dufour-type oscillograph, it used a hot cathode, which allowed a lower anode/cathode voltage (3 kV), and was constructed in a compact and robust manner. Very similar to the Dufour-type oscillograph, the cathode ray was recorded directly onto photographic film. Since the time sweeping of the c.r.t. was achieved by applying a high-frequency periodic voltage at the horizontal deflection plates rather than through a sawtooth voltage, the signal-time displays recorded had to be converted into a scale that was linear with time – a cumbersome task which the user had to perform stepwise and by hand. David A. KEYS, a physicist at McGill University, was the first to succeed in recording pressure-time profiles of underwater explosions with high temporal resolution {KEYS ⇒1921; ⇒Fig. 4.19–C}; he used a Wood-type oscillograph and a tourmaline gauge. KEYS performed these studies on the orders of the British Admiralty.

In parallel with the development of fully electronic oscillographs, *hybrid-type oscillographs* were also constructed. They only included a c.r.t. for vertical deflection; the horizontal deflection was realized mechanically by a rotating drum covered with film paper, onto which the screen of the c.r.t. was imaged. During 1919–1920, DUFOUR³⁵⁹ applied this technique to record low- and medium-frequency waveforms. This recording method was resumed and perfected in Germany. The dynamic gas pressure in fired rifles was successfully recorded in this way using a piezoelectric gauge {JOACHIM & ILLGEN ⇒1932; ⇒Fig. 4.19–D}.

The recording of very fast transient signals using single-shot triggering oscilloscopes was not possible until the advent of phosphors with improved persistence. In addition, a quantum leap in recording high-speed c.r.t. traces occurred upon the invention of high-sensitivity photographic materials, such as the well-known *Polaroid film* {LAND ⇒1948}. Furthermore, electronic storage mesh devices arranged behind the tube's phosphor were developed in the 1960s which allowed one to capture and store transient pictures that could be recorded with conventional still cameras.

A significant milestone was reached with the invention of *digital storage oscilloscopes*, which first became commercially available in the 1970s. These instruments digitize the input signals and store them into digital memories. The key advantages of this approach are that the stored waveform can easily be reviewed on the display at any time, long after the actual original analog signal has disappeared, and that the digitized data can be used directly in subsequent computational analyses.³⁶⁰

Modern *transient recorders* (or *transient digitizers*) that store the data in memories are capable of recording transient wave forms up to very high sampling rates. Combined with general-purpose PC-based instrumentation for data presentation and analysis they form very powerful and versatile data acquisition systems. Due to technological advances, the distinction between transient digitizers and digital oscilloscopes is blurring, and either are being used for recording transient signals in shock and detonation physics.

Triggering. Correct triggering always was and still is one of the most crucial factors in shock wave and explosion research: it is required, for example, to precisely activate pressure gauge amplifiers, cameras and light sources in order to capture the motion of the shock wave in the field of view. During the pioneering period of shock wave research, triggering was a real art. The “Knochenhauer circuit” {KNOCHENHAUER ⇒1858; ⇒Fig. 4.19–E}, a coupling of two high-voltage capacitor discharge circuits, was used by August TOEPLER {⇒1864} to generate a shock wave at a first spark gap and to illuminate the shock wave in the given field of view using a second spark gap fired after an adjustable delay time, which could be as short as tens of microseconds {⇒Fig. 4.18–A}. This first fully electric delay circuit was improved by Ernst MACH and Gustav GRUSS, and they used it in their optical studies of Mach reflection {E. MACH &

³⁵⁹ A.E. DUFOUR: *Oscillographe cathodique*. J. Phys. & Rad. 1 [VI], No. 5, 147-160 (1920).

³⁶⁰ N. BROCK: *Oscilloscopes, analog and digital*. In: (G.L. TRIGG, ed.) *Encyclopedia of applied physics*. VCH, Weinheim/Bergstr., vol. 13 (1995), pp. 37-57.

GRUSS \Rightarrow 1878}. Since then their circuitry has been known as the “Mach circuit” $\{\Rightarrow$ Fig. 4.19–E}.

The appropriate triggering of a mechanically generated shock wave – such as the head wave generated by a supersonic bullet fired from a rifle {E. MACH & SALCHER \Rightarrow 1886} – in the highly sensitive environment of an optical interferometer was even more tricky. Eventually, it was satisfactorily resolved by Ludwig MACH $\{\Rightarrow$ 1896}, Ernst MACH’s oldest son, who combined the fluid dynamic delay with an electric switching method $\{\Rightarrow$ Fig. 4.19–G}. This unique triggering technique was later reused to generate a series of light flashes in a multiple-spark camera {CRANZ & SCHARDIN \Rightarrow 1929; \Rightarrow Fig. 4.19–M}.

In detonics, individual delay times between the initiations of multiple charges can easily be achieved by using a detonation cord. This consists of a core made of a high explosive, usually PETN, surrounded by a waterproof covering. The type most frequently used is Primacord[®], a flexible linear detonating cord manufactured by Dyno Nobel Inc. (Salt Lake City, UT). It detonates with a velocity of about 20,350 ft/s (6.2 mm/ μ s). Much longer delay times can be achieved with the *Bickford fuse* or *safety fuse*, which consists of a central hemp cord surrounded by a core of black powder enclosed in a PE water-resistant cover. Since it is intended for the ignition of black powder charges at rather low rates, it burns at a velocity of about 1 ft/min (5.1 mm/s).³⁶¹

It was soon recognized by shock experimentalists that a rectangular current pulse of any desired duration is very useful for solving many trigger problems. Beginning in the 1940s, mechanical time delay devices like the *Helmholtz pendulum* $\{\Rightarrow$ Fig. 4.19–F}, which were initially used to generate such pulses, were quickly superseded by electronic circuits. For the generation of rectangular current pulses, a simple transmission line consisting either of lumped L,C elements or a coaxial cable was used. Charged up to a DC potential and discharged via a mercury-wetted contact, this provided very steep rectangular current pulses in the microsecond or even the nanosecond regimes. In the analog era, the *monostable multivibrator* (or *monoflop*), a derivative of the *flip-flop* {ECCLES & JORDAN \Rightarrow 1919}, became the most widely used electronic delay generator for “one shot” triggering.³⁶² To obtain a delayed pulse for trigger purposes, an electric pulse derived from the high-speed event was steep-

ened using a *Schmitt trigger circuit* (a useful circuit invented in 1938 by the German engineer Otto H. SCHMITT³⁶³) which started a monoflop. Its rectangular output wave profile, differentiated, rectified and inverted, was applied in order to control a high-speed camera or other diagnostic equipment.

With the arrival of the digital era, however, these analog delay generators were increasingly superseded by IC circuitry, encompassing numerous flip-flop-based digital counters. Today delay generators are already integrated into most electronic multiple-frame cameras for triggering purposes, which makes it much easier to record within the desired time window.

Prerigger Framing Photography. This is a special, extended recording method of real-time cinematography in which the camera continuously records images until the trigger signal is received and the camera is stopped. Depending on the chosen trigger position within the total series of recorded images, the system saves in memory a preselected number of prerigger frames. The high-speed video camera Kodak model 4540 is provided with such a prerigger capability $\{\Rightarrow$ Fig. 4.19–O}. It allows to study unpredictable events, such as the sudden and uncontrolled failure of a structure under dynamic mechanical or thermal loading.

Unpredicted failure mechanisms up to almost 1,000 h can be captured also with *Timelapse Video Recording*, a digital technique which is readily provided with a time/date generator (Victor Company, Japan).

2.8.2 OPTICAL METHODS OF VISUALIZATION: THE KEY TO A BETTER UNDERSTANDING

*Although the schlieren method is only one of the many methods I had to use, it is a very important one, and I believe that you will enjoy the results as much as I do.*³⁶⁴

Ernst MACH
Karl-Ferdinand-Universität
Prague 1887

Photographs are usually taken in reflected light (a method known as “reflected-light photography”) in everyday life, as well as in science and engineering. However, this approach is not directly applicable for shock wave visualization because generally the density jump at the shock front in a

³⁶¹ Primacord and the Bickford fuze were manufactured by the Ensign-Bickford Co. (Simsbury, CT). In 2003, the Ensign-Bickford Co. merged with Dyno Nobel ASA, with the new entity to be called “Dyno Nobel Inc.” (Salt Lake City, UT).

³⁶² B. CHANCE: *Waveforms*. McGraw-Hill, New York (1949), pp. 166–171, 179–182.

³⁶³ O.H. SCHMITT: *A thermionic trigger*. J. Scient. Instrum. **15**, No. 1, 24–26 (1938).

³⁶⁴ Taken from a letter of Ernst MACH to August TOEPLER (dated July 11, 1887) which is now kept in the Archives of the TU Dresden.

transparent fluid cannot be resolved in this way under normal conditions. This also holds for shocks in a solid: most solids are opaque anyway, and the shock wave is hidden somewhere inside. The key to investigating fluid phenomena is to select and apply the optical method that delivers the most appropriate and accurate picture of the most important physical quantities, such as the density and the pressure distributions in the desired direction and at the desired time instant.

Important scientific advances often happen when complementary investigational techniques are brought together. The three basic optical methods – schlieren, shadowgraphy and interferometry – gave early shock researchers their first insights into an abundance of completely new supersonic flow phenomena. These three principal optical techniques of modern flow visualization, which fulfill all of the requirements described above, were invented within the short period 1864 to 1891. However, it is impossible to determine the velocity, pressure and density using only optical experiments; some gas dynamics equations must be applied. If the flow structure (such as the configurations and locations of the shock waves) and the density field (obtained by optical methods) are known, the process of integrating the fluid dynamic equations is greatly simplified.³⁶⁵

Schlieren Methods. The schlieren method was invented by the English natural philosopher Robert HOOKE {⇒1672} and it was used by the French physicist Léon FOUCAULT (1858) to test the optical surfaces of mirrors for use in telescopes. However, August TOEPLER {⇒1864}, a lecturer in physics and chemistry at the Royal Agricultural College in Bonn-Poppelsdorf, Germany, devised a modification of the schlieren method, the “Toepler schlieren method” {⇒Fig. 4.18–A}, which proved most useful in fluid dynamics. From an historical point of view it is remarkable that one of the first applications that TOEPLER used his method for was the visualization of a propagating spark wave – a weak shock wave. TOEPLER’s schlieren method was also used in the famous ballistic experiments performed to visualize the head wave generated by a supersonic projectile [E. MACH & SALCHER ⇒1886], and in the study of high-pressure free air jets [SALCHER & WHITEHEAD ⇒1889].

TOEPLER’s classical schlieren method is a two-dimensional technique; *i.e.*, it is only capable of measuring the total de-

viation of a light beam that passes through a test section containing the gas under study. Consequently, there is no way to separate out the effects of density gradients at different positions in the test section. This disadvantage was overcome by the invention of a “three-dimensional schlieren system” that uses pulsed laser holography [BUZZARD ⇒1968].

Color schlieren methods {⇒Fig. 4.18–B} are increasingly used in shock tube and wind tunnel facilities to visualize supersonic flows. Color schlieren photography is not only more appealing to the eye, but it also facilitates analysis. Its principle, devised in 1896 by the London amateur microscopist Julius H. RHEINBERG, was first applied to gas dynamics by the German physicist Hubert SCHARDIN {⇒1942; ⇒Fig. 4.6–I}. The introduction of the “constant deviation dispersion prism,” which was positioned between the white light source and the first schlieren lens, stimulated the application of the color schlieren method to fluid dynamics [HOLDER & NORTH ⇒1952; ⇒Fig. 4.18–B]. This resulted in a variety of new modifications being proposed and applied by others. Further examples of color schlieren pictures taken by different methods are shown in Figs. 4.5–M, N.

Shadowgraphy. The shadowgraph method was invented at the University of Agram, Austro-Hungarian Empire (now Zagreb, Croatia) by the physics professor Vincenz DVOŘÁK, who was one of Ernst MACH’s assistants at the Charles University in Prague during the period 1871–1875 [DVOŘÁK ⇒1880; ⇒Fig. 4.18–C]. Widely applied by the English physicist and inventor Charles V. BOYS, this technique considerably simplified the visualization of supersonic flows in ballistic testing ranges, where it has since become a standard technique [BOYS ⇒1890; ⇒Fig. 4.6–H]. Using an intense pulsed point light source (*e.g.*, a Libessart spark) and a retroreflective background (*e.g.*, a Scotchlite screen) positioned at a distance several meters away from the spark, it is even possible to obtain shadowgraphs from large objects moving at high speed with sufficient film exposure [EDGERTON ⇒1958; ⇒Fig. 4.18–D].

A detailed historical review of schlieren and shadowgraph techniques was given recently [SETTLES ⇒2001].

Interferometry. Historically, interference phenomena were used to establish the nature of light.³⁶⁶ The first interference phenomena to be noticed, the colors exhibited on soap bubbles and thin films on glass surfaces, were studied on a scientific basis by Robert BOYLE (1664), Robert HOOKE (1672)

³⁶⁵ S.M. BELOTSEKOVSKY: *Anwendungsmöglichkeiten und Perspektiven optischer Methoden in der Gasdynamik*. In: (N.R. NILSSON and L. HÖGBERG, eds.) *Proc. 8th Int. Congress on High-Speed Photography*. Almqvist & Wiksell, Stockholm, and Wiley, New York *etc.* (1968), pp. 410–414.

³⁶⁶ M. BORN and E. WOLF: *Principles of optics*. Pergamon Press, London *etc.* (1959).

and Sir Isaac NEWTON (1672 & 1675), who studied “Newton rings.” Subsequent studies of the superposition of two beams of light resulted in numerous interferometer constructions, most of them invented and applied in the second half of the 19th century {JAMIN \Rightarrow 1856; Armand H.L. FIZEAU 1862; Albert A. MICHELSON 1881; ZEHNDER \Rightarrow 1891; L. MACH \Rightarrow 1891; Lord RAYLEIGH 1896; Charles FABRY & Alfred PÉROT 1899}. In particular, the *Jamin interferometer* {JAMIN \Rightarrow 1856}, the prototype for many subsequent interferometer techniques, paved the way for interferometry to be used as a diagnostic tool in fluid dynamics. First used to measure the amplitude of acoustic waves at the threshold of hearing {A. TOEPLER & BOLTZMANN \Rightarrow 1870; \Rightarrow Fig. 4.18-E} – a masterpiece of experimental physics which demonstrated the enormous sensitivity of this method – it must have also stimulated Ernst MACH to apply this method to scan the (previously unknown) density profile at the shock front of a “spark” wave, a weak aerial shock wave generated by discharging a Leiden jar {E. MACH & von WELTRUBSKY \Rightarrow 1878; \Rightarrow Fig. 4.18-E}.

Independently, Ludwig MACH at Charles University in Prague and Ludwig ZEHNDER at Würzburg University improved the Jamin interferometer and came up with a new configuration, now known as the “Mach-Zehnder interferometer” { \Rightarrow Fig. 4.18-F}. Advantageously, it allows the object beam and the reference beam to be separated by a large distance. Ludwig MACH { \Rightarrow 1896} subsequently also demonstrated the great potential of interferometry by visualizing the flow around a supersonically flying bullet and obtaining quantitative data for the region behind the shock wave in a subsequent analysis, which was an important milestone in fluid dynamics and high-speed diagnostics. His next impressive application was the interferometric recording of free air jets at high speed {L. MACH \Rightarrow 1897}. Since the Mach-Zehnder interferometer measures variations in refractive index, and hence in density, it is particularly appropriate for flow visualization studies in ballistic tunnels, shock tubes and wind tunnels.³⁶⁷

Other Methods. Other ingenious – albeit rather exotic – methods for optically visualizing the propagation of shock waves have been applied for special applications. Examples include:

- ▶ *pulsed-laser holography*, a technique for recording high-speed events during the duration of the laser pulse. For example, in fluid dynamics it can be applied to measure the size, position, displacement and velocity of particles in a flow field and allows a shock wave to be recorded in three dimensions {GABOR \Rightarrow 1947; BROOKS ET AL. \Rightarrow 1966; LAUTERBORN ET AL. \Rightarrow 1972; \Rightarrow Fig. 4.18-G};
- ▶ various surface-supported *optical reflection techniques*, which allow the instant of arrival of a shock wave at the surface of an (opaque) solid to be visualized {FEOKTISTOVA \Rightarrow 1960; FOWLES & ISBELL \Rightarrow 1965; \Rightarrow Fig. 4.13-L};
- ▶ *moiré techniques*, which, for example, are useful for visualizing the displacement fields of impacted bodies, the movements, deformations and vibrations of a model in a wind tunnel, or the propagation of plastic waves in shock-compressed solids {KORBEE ET AL. \Rightarrow 1970};
- ▶ *laser speckle photography*, a noncontact technique that relies on the speckle effect produced when laser light is scattered at a diffusing surface. The method is suitable for measuring displacement components of specimens with rough surfaces as well as the density fields of compressible fluid flows over a wide dynamic range, such as those generated by the Mach reflection of shock waves and by thermal convection;³⁶⁸
- ▶ *dynamic photoelasticity*, a method for visualizing stress and fracture in dynamically loaded model structures {MAXWELL \Rightarrow 1850};
- ▶ *surface thermography*, a global and nonintrusive technique that uses color paints, liquid crystals or infrared cameras and is particularly suited for hypersonic flow and reentry studies {KLEIN \Rightarrow 1968; \Rightarrow Fig. 4.18-H};
- ▶ *smoke flow visualization*, a unique method for visualizing supersonic flow {GODDARD \Rightarrow 1959}; and
- ▶ *particle tracer analysis*, an outgrowth of Vincent P. GODDARD’s method which allows the reconstruction of physical properties of large spherical explosions in free air when combined with high-speed photography of smoke trail tracers introduced into the ambient gas immediately before the arrival of the shock wave {CDRE Suffield \Rightarrow 1964; \Rightarrow Fig. 4.16-Q}.

³⁶⁷ R. LADENBURG and D. BERSHADER: *Interferometry*. In: *High speed aerodynamics and jet propulsion*. Oxford University Press, London; vol. IX (1955): (R.W. LADENBURG, B. LEWIS, R.N. PEASE, and H.S. TAYLOR, eds.) *Physical measurements in gas dynamics and combustion*, pp. 47-78.

³⁶⁸ M. KAWAHASHI and H. HIRAHARA: *Velocity and density field measurements by digital speckle method*. Opt. Laser Technol. **32**, 575-582 (2000).

2.8.3 THE SOOT TECHNIQUE: INGENIOUS ‘BLACK MAGIC’

*If the sound [shock] waves are the originators of the [Antolik] soot figures, then it should be possible to use them to study shock reflection. This is indeed the case.*³⁶⁹

Ernst MACH
Karl-Ferdinand-Universität
Prague 1875

The soot technique, discovered by chance in the early 1870s by the Hungarian schoolmaster Károly ANTOLIK, is both a visualization and recording method {ANTOLIK \Rightarrow 1874; \Rightarrow Fig. 4.5–C}. However, although it is amazingly simple to use, it is not so easy to understand the mechanism by which soot is removed behind shock and detonation wave interactions. This aroused the curiosity of various researchers to investigate this phenomenon in more detail such as by applying high-speed cinematography {CRANZ & SCHARDIN \Rightarrow 1929; SCHULTZ-GRUNOW \Rightarrow 1969}.

In contrast to the visualization methods discussed above, the soot method is a time-integrating recording method; *i.e.*, it is not capable of taking snapshots of propagating and interacting shock waves but is instead limited to reproducing irregular shock reflection phenomena as irreversible traces of the triple points in the soot, known as “triple point trajectories.” However, by ingeniously using an anti V-arrangement (*i.e.*, two V-arrangements facing each other { \Rightarrow Fig. 4.5–D}), Ernst MACH and Jaromir WOSYKA { \Rightarrow 1875} were able to show for the first time that it is possible to capture the motion of two Mach disks colliding head-on. The disks were stopped and reproduced as a thin line of piled-up soot, thus making the width of the Mach disk visible in the plane of symmetry: an unusual and simple but ingenious way to visualize a supersonic phenomenon without using expensive high-speed photographic instrumentation!

The soot method has also been used successfully to record the cellular nature of the detonation front in gaseous explosive mixtures, for example by simply blackening the inner wall of the reaction vessel.³⁷⁰ Recently, the soot technique even proved useful for recording detonation phenomena in dust explosions { \Rightarrow Fig. 4.16–U}. Soot-covered foils have also been used to characterize the regular cellular structure of a detonation. This cellular structure – a pattern of multiple V-arrangements, like that observed by MACH and ANTOLIK in

the case of interacting shock waves – is inscribed by the triple points of transverse waves interacting in the detonation wavefront.

ANTOLIK’s soot technique can also be adapted to record shock interactions at higher pressure levels by increasing the adhesion of the soot particles, *e.g.*, by sandblasting the glass plates prior to applying the soot layer. This procedure even allows one to record double Mach reflection, which results in two concentric soot funnels { \Rightarrow Fig. 4.5–F}: at transition point P_T at which *Double Mach Reflection (DMR)* turns into *Single Mach Reflection (SMR)* they merge into a single soot funnel.

Recently, Japanese researchers explored an explanation of detonation soot track formation and compared it with previous hypothesis of formation mechanism. Investigating soot track formation numerically, they assumed that the soot tracks were due to variations in the direction and magnitude of the shear stress created by the boundary layer over the soot foil.³⁷¹

2.8.4 HIGH-SPEED PHOTOGRAPHY AND PHOTONICS: FREEZING THE INSTANT

*In the month of June last a successful experiment was tried at the Royal Institution, in which the photographic image was obtained of a printed paper fastened upon a wheel, the wheel being made to revolve as rapidly as possible during the operation. From this experiment the conclusion is inevitable, that it is in our power to obtain the pictures of all moving objects, no matter in how rapid motion they may be, provided we have the means of sufficiently illuminating them with a sudden flash.*³⁷²

Henry Fox TALBOT
Lacock Abbey 1851

The advancement of high-speed photography has always been crucial to detailed analyses of shock and detonation effects and applications of them. In this regard, Ernst MACH’s scientific way of experimenting was very successful and instructive to his contemporaries. He was not only an eminent philosopher of science, but he can also be regarded as being the first gas dynamicist and high-speed photographer, who carried out his shock and explosion research according to the motto *Sehen heißt verstehen* (“seeing is understanding”).

³⁶⁹ E. MACH and J. WOSYKA: *Über einige mechanische Wirkungen des elektrischen Funkens*. Sitzungsber. Akad. Wiss. Wien **72** (Abth. II), 44–52 (1875).

³⁷⁰ R.I. SOLOUKHIN: *Shock waves and detonations in gases*. Mono Book Co., Baltimore (1966).

³⁷¹ K. INABA, M. YAMAMOTO, J.E. SHEPHERD, and A. MATSUO: *Soot track formation by shock wave propagation*. ICCES **4**, No. 1, 41–46 (2007).

³⁷² W.H.F. TALBOT: *On the production of instantaneous images*. Phil. Mag. **3** [IV], 73–77 (1852).

The challenge of attempting to record dynamic events in compressible gas flows encouraged the development of new high-speed photographic equipment which, in turn, enabled the discovery of new shock phenomena. During the pioneering period of such research, gas dynamicists were often also high-speed photographers who invented, developed, built, applied and improved their own equipment.

Single-Shot Photography. Snapshot photography of a dynamic event was first demonstrated by the English chemist and pioneer photographer W. Henry Fox TALBOT {⇒1851}. However, the complicated process he used to prepare and develop the film did not permit its immediate application to ambitious plans to freeze the motions of events occurring at supersonic speeds. Since high-speed films were not yet available to August TOEPLER {⇒1864}, he visualized shock waves subjectively using a stroboscopic set-up – a curiosity in the early history of fluid dynamics. With the advent of highly sensitive gelatin dry plates {MADDOX ⇒1871} and electric spark light sources of a high intensity but a short duration (about 1 μ s or less), it became possible to both capture the motions of propagating aerial shock waves with practically no motion blur, and to obtain a sufficient exposure density on photographic film. The first photographed shock wave was generated by the discharge of a Leiden jar, visualized with the schlieren method, and photographed on a gelatin dry plate {E. MACH & WENTZEL 1884; E. & L. MACH ⇒1889; ⇒Fig. 4.5–G}.

High-Speed Cinematography. The evolution of high-speed photography, ranging from single-shot photography to high-speed cinematography, is a story of its own {e.g., RAY ⇒1997}, but a few milestones can be mentioned here. The *rotating mirror* {⇒Fig. 4.19–I}, a mechanical device for resolving the motion of an object in one dimension, was apparently first used in England by Sir Charles WHEATSTONE {⇒1834}, the legendary inventor of the Wheatstone bridge.³⁷³ The rotating mirror was first used in Germany for resolving the propagation and reflection of detonation waves in gaseous combustible mixtures {⇒Fig. 4.19–K}. This principle of streak recording was later adopted in England and became known under the name *wave speed camera* {PAYMAN & WOODHEAD ⇒1931; ⇒Fig. 4.19–L}.³⁷⁴ It is in-

teresting here to note that this task was not set by military needs – unlike most high-speed diagnostic techniques developed over the following decades – but was rather initiated by safety considerations, namely attempts to better understand the mechanism of firedamp explosions in coal mines and thus to initiate more effective preventive measures. In the United States, the streak recording technique that used rotating mirror cameras was primarily applied in basic detonation research to better understand the ultrafast processes of initiation and propagation in detonating condensed high explosives as well as for the routine testing of high explosives and detonators {⇒Figs. 4.17–P, Q, R}.

High-speed cinematography reached its first peak with the invention of the *Cranz-Schardin multiple-spark camera* {CRANZ & SCHARDIN ⇒1929; ⇒Fig. 4.19–M}. This was a big step forward in the evolution of high-speed photography, because the new device immediately allowed one to resolve high-speed events at 300,000 frames per second for a total of eight frames, which was soon extended to the present-day standard of 24 frames. Based on a unique recording principle that permits almost any frame rate desired to be realized and almost any type of pulsed light source of small dimension to be used, it was later also modified into cineradiography using a number of flash X-ray tubes {TSUKERMAN & MANAKOVA ⇒1957; CHANG ⇒1983}.

The ambitious U.S. program of atomic weapons development and testing during and after World War II resulted in the further development of *mechanical framing cameras* with high and ultrahigh frame rates (up to some 10^6 frames/s) {⇒Figs. 4.17–P, R}. In addition, the various requirements of dynamic plasma diagnosis in numerous fusion research programs stimulated new developments in *ultrafast image tube camera technology*, particularly in the United States, England, France, and the former Soviet Union. With the advent of the *microchannel plate (MCP)* in the 1980s – a U.S. invention based on the electron multiplier {FARNSWORTH ⇒1930} – a new optoelectronic device with excellent gating capability in the low nanosecond regime and high light intensification became available that could be combined very successfully with the preexisting *charge-coupled device (CCD)*, a U.S. invention {BOYLE & G.E. SMITH ⇒1969}. This resulted in the *Intensified CCD (ICCD)* which, when applied in a multiple arrangement with optical image splitting, created a new generation of *ultrafast multiple digital framing cameras* that are useful for recording all kinds of shock wave, detonation and impact phenomena {Hadland Photonics Ltd. ⇒1993}.

³⁷³ The Wheatstone bridge, operated in a pulsed mode and modified to eliminate large D.C. offset voltages, has become an important device for supplying a rectangular current pulse for all kinds of piezoresistive shock pressure gauges.

³⁷⁴ W. PAYMAN: *The wave-speed camera*. Safety of Mines Research Board (SMRB), U.K., Papers Nos. 18 and 29 (1926).

2.8.5 FLASH X-RAY TECHNIQUES: VISUALIZING THE HIDDEN

It was a lucky chance that even before the beginning of war it occurred to STEENBECK, while studying pulsed gas discharges at low pressure at the Siemens Company, to investigate the emitted X-radiation in more detail. It showed that it was sufficiently intense to expose photographic plates within a fraction of a microsecond. STEENBECK visited me on July 25, 1938, asking whether such short and intense flash X-rays would not be of great importance in ballistics, and proposing cooperation...Of course, the most important of these applications became the revelation of the hollow charge effect.³⁷⁵

Hubert SCHARDIN
Technische Akademie der Luftwaffe
Berlin-Gatow 1938

Radiography (in optical terms a shadowgraph method) has been around since Wilhelm C. RÖNTGEN's spectacular X-ray experiments at Würzburg University in 1895.³⁷⁶ However, capturing the motions of high-rate phenomena – particularly those of shock and detonation waves with velocities of up to almost 10,000 m/s and jets from shaped charges with velocities of up to 12,000 m/s – requires X-ray pulses of submicrosecond duration, which also need to be of a very high intensity in order to provide a sufficient exposure density on the film. Unfortunately, however, pulsed X-ray sources that fulfilled these two requirements were not available to shock and explosion researchers until the 1960s. Curiously enough, this urgently required diagnostic method, which was later called “flash radiography,” was then invented almost simultaneously by the German physicist Max STEENBECK {⇒1938} at Siemens AG in Berlin and the U.S. physicists Kenneth H. KINGDON and H.E. TANIS {⇒1938} at General Electric Co. in Schenectady, NY.

Flash Radiography. During World War II, flash radiography rapidly grew into an important diagnostic tool for detonics and the first flash X-ray systems using vacuum discharge tubes became commercially available: in Germany by Siemens AG (Berlin) and in the U.S.A. by Westinghouse Elec-

tric Corporation (Bloomfield, NJ). Flash X-ray systems using pure field emission tubes were produced not until the late 1950s by Field Emission Corporation (McMinnville, OR). During the war flash radiography was particularly applied in Germany to secret military studies of shaped charges. Later it became the preferred (and often the only applicable) method of visualizing nuclear implosion bomb assemblies and laser fusion experiments. Applications in detonation physics considerably stimulated advances in precision detonation techniques and the development of other high-intensity pulsed radiation sources too. Modern commercially available flash X-ray systems cover the range from 75 kV to 2 MV. Exotic examples include pulsed electron beam machines, flash neutron radiography using pulsed nuclear reactors, and high-voltage linear electron accelerators such as the PHERMEX facility at the Los Alamos Scientific Laboratories {VENABLE & BOYD ⇒1965}.³⁷⁷

Unlike optical methods, flash radiography is insensitive to the self-luminous events that accompany all detonation processes, and the smoke resulting from detonation products cannot obscure the test object when using this technique. In addition, X-rays provide insight into the interiors of shock-loaded solids and make it possible to measure temporal shock front positions. These particular properties of flash X-rays allowed phenomena connected with the emission of very bright light that had previously not been accessible to optical methods to be visualized for the first time, for example:

- ▶ the creation of shock waves emerging from exploding wires during the very initial stage of wire explosion;
- ▶ the formation of jets in shaped charges;
- ▶ the propagation of detonation fronts in liquid and solid high explosives, and even in gases, and
- ▶ the contact areas of objects that impact at high velocities.

Furthermore, it also became possible to visualize shock wave propagation and interaction phenomena in optically opaque media (*i.e.*, the majority of solids), and to quantitatively determine the density jump across the shock front using photodensitometry. This was first demonstrated not only in high-density matter, such as in liquids and solids {SCHALL ⇒1950}, but also in various gases using high X-ray-absorbing additives {SCHALL & THOMER ⇒1951}. In the 1950s, *flash soft radiography*, a technique which is also particularly well-suited to visualizing density variations in low-density matter, was developed. This technique uses special X-ray tubes that preferably emit an intense soft X-ray spectrum, and it combines highly sensitive X-ray films with

³⁷⁵ H. SCHARDIN: *Über die Entwicklung der Hohlladung*. Wehrtech. Monathefte 51, Nr. 4, 97-120 (1954).

³⁷⁶ It is interesting to note here that only one year after his famous discovery of X-rays, RÖNTGEN made a radiograph of a firearm – his personal rifle – which (together with numerous handwritten comments) he sent to his friend Franz S. EXNER, a professor of physics at the University of Vienna and pioneer of modern physics. However, RÖNTGEN's technique only allowed him to take radiographs of objects at rest. See O. GLASSER: *Wilhelm Conrad RÖNTGEN und die Geschichte der Röntgenstrahlen*. Springer, Berlin etc. (1995), pp. 272-273.

³⁷⁷ L.E. BRYANT (ed.): *Proceedings of the Flash Radiography Symposium* [Houston, TX, Sept. 1976]. The American Society for Nondestructive Testing, Columbus, OH (1977).

high-conversion-efficiency intensifying screens. This allowed shock waves in gases of low atomic numbers to be visualized, even without using X-ray-absorbing additives {HERRMANN \Rightarrow 1958}.

Numerous examples of various applications of flash X-ray diagnostics are provided in the PICTURE GALLERY { \Rightarrow Figs. 4.5–H; 4.8–F, G, H, I; 4.13–H; 4.14–T; 4.15–B; 4.16–O}.

Flash X-Ray Diffraction Analysis. X-ray diffraction, a technique first established to analyze the fine structure of unloaded crystalline materials (M. VON LAUE 1912; W.H. BRAGG 1912; P.J.W. DEBYE and P. SCHERRER 1916), and later extended to statically loaded targets, was also extended to measure the lattice compression of crystals *during* shock compression, by applying high-intensity flash soft X-ray pulses of submicrosecond duration – preferably characteristic (or line) radiation such as Cu-K α and Mo-K α . This new and important method, known as “flash X-ray diffraction,” was combined with a precisely triggerable planar shock compression technique, thus providing the first insights into the microscopic regime of a shock-loaded crystal lattice. However, flash X-ray diffraction is presently limited to single- and polycrystalline substances of low atomic number only, and it focuses on the region immediately behind the shock front. Spectacular demonstrations using flash X-ray diffraction have provided evidence that phase transformations can occur on nanosecond timescales in shock-compressed solids {JOHNSON ET AL. \Rightarrow 1970 & 1972}. Furthermore, the first flash X-ray diffraction patterns obtained from an aluminum shaped charge indicated that the high-velocity jet (6.4 km/s) consists of a particulate solid – *i.e.*, it has not fully transformed into a molten state {JAMET & THOMER \Rightarrow 1975; GREEN \Rightarrow 1975}.

In the early 1990s, an even more advanced experimental technique was applied in England, which used a high-power pulsed laser to simultaneously shock-compress the target and generate an intense soft X-ray pulse for diffraction purposes {WARK ET AL. \Rightarrow 1991}. In the late 1990s, some classic flash X-ray diffraction experiments of the 1970s were performed on essentially the same crystal types at Washington State University {RIGG & GUPTA \Rightarrow 1998}, although a number of worthwhile technical improvements were made and the loading conditions of the target under planar impact were carefully reevaluated. These studies resulted in a better understanding of the compression of the unit cell under planar shock waves.

2.8.6 THE CORRECT MEASUREMENT OF SHOCK PRESSURE: AN EVERGREEN PROBLEM

*There are perhaps few questions upon which, till within quite a recent date, such discordant opinions have been entertained as upon the phenomena and results which attend the combustion of gunpowder. As regards the question alone of the pressure developed, the estimates are most discordant, varying from the 1000 atmospheres of ROBINS to the 100,000 atmospheres of RUMFORD...*³⁷⁸

Sir Andrew NOBLE
W.G. Armstrong & Co., Elswick
Sir Frederick A. ABEL
British War Dept., London
1874

Pressure, temperature and density (or specific volume, the reciprocal value) are all basic quantities used to describe the thermodynamic state of matter. A knowledge of the pressure is also of particular importance when characterizing dynamic processes.

In ballistics, it allows one to estimate the time-dependent force exerted on the base of the projectile by the propellant gases during its passage through the barrel. Using the Second Law of Motion {Sir NEWTON \Rightarrow 1687}, the acceleration of the projectile and its velocity at the moment that it leaves the muzzle (“ v_0 ,” an important ballistic quantity for gunners) can be determined.

In shock wave physics, the pressure-time profile $p(t, R)$ allows one to determine the mechanical impulse I in the blast field of an explosion at a distance R using a simple integration procedure given by $I(t, R) = \int p(t, R) dt$. The knowledge of the impulse that acts on a structure positioned at R is an important quantity that is used to estimate the damage caused to structures exposed to blast waves.

In classical percussion, the percussion pressure – defined in terms of the normal percussion force per contact area – can be very large, because the short-acting force of percussion is typically already quite large and the contact area is small in “hard” percussion partners, such as those for a metal plate hit by a hammer via a lathe center or a sharp-edged chisel.

In aerodynamics, the *total pressure* or *stagnation overpressure* p that is recorded by a gauge placed face-on to a blast wave is equal to $\rho v^2 f_p (M)$, where v is the particle flow velocity, ρ the gas density and f_p is a pressure coefficient. It is difficult to determine p by measuring ρ and v because f_p

³⁷⁸ A. NOBLE and F.A. ABEL: *Researches on explosives. Fired gunpowder. Part II.* Phil. Trans. Roy. Soc. Lond. **171**, 50 (1880).

depends on the Mach number $M = v/a$, where a is the velocity of sound.

Pressure gauges should cause as little disturbance as possible to the shock wave flow, and miniaturization was a logical step toward this goal. Since the increase in pressure in a shock wave is accompanied by an increase in temperature, pressure gauges must be shielded or designed in such a way that the sensor element is only pressure-dependent (not temperature-dependent). To a certain extent this is achieved, for example, in the case of piezoresistive gauges by choosing manganin, a metal alloy with a very low temperature coefficient. Furthermore, an ideal pressure gauge should be free of any effects due to stress history (hysteresis) and should have a “bulk-intrinsic” gauge coefficient – *i.e.*, it should be dependent only on the pressure-sensitive material of the gauge and not on the particular gauge geometry. Even piezoelectric and piezoresistive pressure gauges, with their material-dependent piezo coefficients, approach this ideal response only partially and thus require careful analysis of the stress loading conditions applied.

It is small wonder that the measurement of pressure is associated with the earliest efforts of ballisticians as well as percussion, explosion and shock wave researchers who were searching for realistic records of pressure-time profiles under various experimental conditions and within a wide temporal range. The difficult task of constructing appropriate pressure gauges that are inexpensive, small-sized and have high temporal resolution – rise times in the low nanosecond regime are required in shock wave physics and rise times of as little as picoseconds are used in micro shock wave applications – has occupied generations of inventors and researchers, and still does. Although pressure sensors are now a billion-dollar industry (and one that is still growing), only a few companies have specialized in the development of sensors appropriate for use in shock wave diagnostics. The need to record fast pressure-time profiles stimulated the development of not only the gauge technique itself, but also recording devices. In the 1920s, mechanical chronographs were superseded by c.r.t. oscilloscopes {WOOD \Rightarrow 1923}, and today those analog oscilloscopes have been replaced by either digital oscilloscopes or digitizers in most laboratories (*see* Sect. 2.8.1).

The use of pressure gauges capable of recording shock pressures in all states of aggregation has grown into a special branch of diagnostics and is almost as complex and bizarre as shock wave physics itself. Apparently, it has never been reviewed in context. The true time-resolved measurement of shock wave profiles in shock-loaded matter is a difficult task, particularly in solids, because transit times are often very small, which requires techniques with ultrashort response

times. The use of piezoelectric and piezoresistive gauges in solid-state shock wave physics was reviewed up to the early 1970s by William MURRI and associates { \Rightarrow 1974}. Robert A. GRAHAM³⁷⁹ and James R. ASAY, two Sandia shock physicists, reviewed diagnostic methods (optical, capacitive, piezoelectric and piezoresistive) developed up to 1978 to measure shock wave profiles in solids. Various designs of pressure gauges are now used routinely in large numbers. However, with the steady refinement of numerical models developed in dynamics materials science over the last few decades, measured pressure data have increasingly become the subject of critical analyses {GUPTA ET AL. \Rightarrow 1980}. Experimental techniques used to measure pressures in blast waves were reviewed in 2001 by John M. DEWEY, a noted Canadian shock physicist {DEWEY \Rightarrow 1964}. Some developments, which are also given in the CHRONOLOGY and in the PICTURE GALLERY, will be summarized in the following.

Mechanical Gauges. Diaphragm sensors that measure pressure through the elastic deformation of a diaphragm – such as that of a membrane, a plate or a capsule – are particularly well suited to mechanically measuring dynamic pressures. When directly coupled with a mechanical chronograph, they were used almost exclusively in the 19th century to record pressure-time profiles of rapid events. Membranes tend to eigen vibrations and hence tend to modify the pressure signal transmitted. These natural oscillations can be damped, but this measure would also reduce the displacements of the membrane – compensation by electronic amplifiers was not possible at that time.

Examples of early pressure recording using membranes that are described in this book include:

- ▶ blast-wave profiles from large explosions of gunpowder in the open air {WOLFF \Rightarrow 1899; \Rightarrow Fig. 4.17–M};
- ▶ primary and secondary pressure pulses emitted from underwater explosions {BLOCHMANN \Rightarrow 1899; \Rightarrow Fig. 4.16–D}; and
- ▶ detonation pressures for firedamp or other combustible gases {MALLARD & LE CHÂTELIER \Rightarrow 1883; \Rightarrow Fig. 4.17–C}, or for solid explosives detonating in a closed reaction vessel {BICHEL \Rightarrow 1898; \Rightarrow Fig. 4.17–D}.

Although mechanical gauges have rather large rise times (in the millisecond regime), they can provide fairly good results for large explosions which produce long-duration pressure pulses.³⁸⁰

³⁷⁹ R.A. GRAHAM and J.R. ASAY: *Measurement of wave profiles in shock-loaded solids*. High Temperatures, High Pressures **10**, 355–390 (1978).

³⁸⁰ According to *Hopkinson scaling* {B. HOPKINSON \Rightarrow 1915}, an observer, stationed at a distance λR from the center of an explosive source with a charac-

In the mid-19th century, mechanical gauges for recording peak pressures of high-rate events were developed mostly for ballistic purposes. The famous *Rodman gauge* {RODMAN \Rightarrow 1857; \Rightarrow Fig. 4.17–K} consists of an indentation tool that is placed into a hole bored into the powder-chamber of a gun or fastened in the base of the shot. The *crusher gauge* { \Rightarrow NOBLE 1872; \Rightarrow Fig. 4.17–K}, an improvement of the Rodman gauge, is based on the deformation of a metal (copper) cylinder. Both gauges were first calibrated with static means and then used to measure the peak pressure in the bore of a fired gun.³⁸¹ Crusher gauges based on the principle of the deformation of a ball by a pressure-driven piston saw a renaissance in World War II; for example, they were used extensively in Operation CROSSROADS { \Rightarrow 1946}, which comprised two nuclear events that were designed primarily to provide information on the effects of atomic bombs on naval vessels. These gauges were deployed at various water depths near ships and on hulls.

Weight- or spring-loaded devices, similar in construction to the safety valves used in steam-boilers {PAPIN \Rightarrow 1679; \Rightarrow Figs. 4.7–A, B}, were used by early ballisticians and chemists, for example to measure the peak pressure of fired gunpowder {Count VON RUMFORD \Rightarrow 1797; \Rightarrow Fig. 4.17–A}; to compare different qualities of gunpowder in regard to their “brisance” { \Rightarrow Fig. 4.17–E}; and to evaluate peak detonation pressures in various combustible gaseous mixtures {BUNSEN \Rightarrow 1857; \Rightarrow Fig. 4.17–B}.

Piezoelectric Gauges. The *direct piezoelectric effect* {CURIE Bros. \Rightarrow 1880} – i.e., the generation of an electric charge in a crystal or a ceramic by subjecting it to a mechanical stress – has been used since the early 1920s to measure pressure-time profiles of dynamic events. *Piezoelectric pressure gauges* typically feature high-frequency response and are particularly useful for recording shock waves. Examples of recorded pressure-time profiles described in this book include:

- ▶ pressure pulses emerging from an electrolytic gas detonation {KEYS \Rightarrow 1921};
- ▶ shock waves resulting from an underwater explosion {KEYS 1923, see KEYS \Rightarrow 1921; WOOD \Rightarrow 1923; \Rightarrow Fig. 4.19–C};
- ▶ gas pressure histories in fired rifles {JOACHIM & ILLGEN \Rightarrow 1932; \Rightarrow Fig. 4.19–D};

- ▶ blast pressure histories in the areas around detonating solid explosives {CROW & GRIMSHAW \Rightarrow 1932};
- ▶ gauge calibration in shock tube studies {REYNOLDS \Rightarrow 1943}; and
- ▶ studies of interactions of high-energy laser pulses with solid targets {JONES \Rightarrow 1962; KREHL ET AL. \Rightarrow 1975}.

Early researchers favored tourmaline crystals because of their high piezoelectric coefficient. Today piezoelectric gauges based on quartz and various piezoelectric ceramics dominate the market and are mainly used in acoustics and gas dynamics. In addition, polyvinylidene fluoride (PVDF) foils {KAWAI \Rightarrow 1969} are becoming increasingly popular in shock wave diagnostics, because this inexpensive material has a very short response time in the nanosecond regime. Advantageously, it can be formed into a variety of shapes to suit special applications. Modern needle hydrophones use very thin PVDF foils. Because of their high upper frequency limit of several MHz, they are also appropriate for diagnosing weak shock waves in water { \Rightarrow Fig. 4.1–Z}.

The *indirect or inverse piezoelectric effect* (CURIE Bros. 1881) – i.e., the generation of a mechanical stress in a crystal or a ceramic by subjecting it to an applied voltage – is utilized in piezoelectric shock wave generators that are used in extracorporeal shock wave lithotripsy. Typically, hundreds of small oscillatory piezoceramic crystals (that are arranged hemispherically and pulsed via an electric discharge) generate pressure pulses which are focused onto a small zone of about one square centimeter.

Piezoresistive Gauges. The *piezoresistive effect* is the change in the resistivity of certain materials due to the application of mechanical strain and was discovered in 1856 by Lord KELVIN. The first *piezoresistive pressure gauge* – a manganin pressure gauge – was apparently constructed by the U.S. physicist Percy W. BRIDGMAN { \Rightarrow 1911}, who made piezoresistive measurements on several polycrystalline metals under static high pressures {BRIDGMAN \Rightarrow 1925}. He later also outlined the formal nature of the piezoresistive effect in single crystals. George HAUVER and coworkers at BRL, Aberdeen Proving Grounds seem to have been the first to exploit the piezoresistive nature of materials to measure pressure in a shock-loaded sample, using a thin disc of sulfur {HAUVER \Rightarrow 1960}. Researchers in England {FULLER & PRICE \Rightarrow 1962} and independently in the United States {BERNSTEIN & KEOUGH \Rightarrow 1964} first used manganin gauges to measure the longitudinal stress in a shock-loaded sample under uniaxial stress. Standard carbon composition resistors

teristic dimension λd will feel a blast wave of the same amplitude P from an explosive charge of dimension d detonating at distance R , but an increased positive pulse duration λT {BAKER, WESTINE & DODGE \Rightarrow 1973}.

³⁸¹ A historical review of gauges for explosive pressure measurement and recording up to 1906 was given by J.E. PETAVEL: *The pressure of explosions – experiments on solid and gaseous explosives. Parts I and II*. Phil. Trans. Roy. Soc. Lond. **A205**, 357–398 (1906).

like those used in electronics have also been used as inexpensive piezoresistive gauges to measure shock pressures {WATSON \Rightarrow 1967}. In 1967, the first attempts were made to measure the lateral stress in a shock-loaded sample {BERNSTEIN ET AL. \Rightarrow 1967} – a difficult task which has been the subject of much debate among shock researchers since then {GUPTA ET AL. \Rightarrow 1980}.

Whereas piezoelectric gauges are primarily used to measure shock pressures in gases and liquids, piezoresistive gauges dominate pressure diagnostics in solid-state shock wave physics. Because of their very short rise time, their small size, low impedance and moderate price, they are ideal sensors for measuring shock pressures, particularly in a noisy environment and in destructive “one-shot” shock experiments. Comparative measurements of the piezoresistive coefficients of various semiconductors have indicated that the gauge factors of C, Ge and Si could be 10–20 times larger than those based on metal films. However, semiconductors have a nonlinear pressure-resistivity characteristic and are more temperature-dependent than standard metal foil gauges. Therefore, they are only used for special applications, such as in “carbon gauges,” which use a thin graphite film encapsulated between two Kapton foils. They also proved useful for measuring pressures in weak shock waves in gas dynamics { \Rightarrow Fig. 4.12–C}.

Examples of Other Methods. One unusual *direct method* of pressure measurement is the ruby fluorescence pressure gauge. It makes use of the fact that the fluorescence of some refractory phosphor materials – such as ruby and alexandrite – is pressure-dependent. The wavelength of the fluorescent emission is linearly dependent upon the pressure from about 1 MPa to 43 GPa (0.01–430 kbar). This linearity up to very high pressures makes the ruby gauge a particularly attractive measurement technique in shock wave physics. Unfortunately, however, the wavelength shift also depends upon the temperature {HORN & GUPTA 1986, *see* BARNETT \Rightarrow 1973}. The ruby pressure gauge may be very useful for measurements performed at extremely high pressures or within harsh chemical environments, where traditional elastic-member deformation techniques cannot be applied.

There are many *indirect methods* of pressure measurement; some examples are given in this book:

- ▶ Ernst MACH used a Jamin interferometer to measure the density jump at the front of an aerial shock wave generated by a spark discharge {E. MACH & VON WELTRUBSKY \Rightarrow 1878; \Rightarrow Fig. 4.12–A}. His son Ludwig MACH applied this method to measure the jump in air

density generated by firing a supersonic projectile from a rifle {L. MACH \Rightarrow 1896; \Rightarrow Fig. 4.6–L}. By converting density data into pressure data using equation-of-state data, he found that the peak pressure jumps at the head wave and tail wave are about +0.2 bar and –0.085 bar, respectively.

- ▶ It is possible to determine the shock front velocity U from a series of flash radiographs and the compression ratio ρ_1/ρ_0 at the shock front using photodensitometry. a combination of the Rankine-Hugoniot equations allows one to determine the shock pressure p_1 {HUGONIOT \Rightarrow 1887, *see* Eq. (14)} at selected moments in time. Examples of flash radiographs are given in the PICTURE GALLERY { \Rightarrow Figs. 4.5–H, 4.8–F to I, 4.13–H, 4.14–T, 4.15–B, 4.16–O}.
- ▶ Some of the authors have also included photodensitometer curves of shock-compressed matter in their publications. On the other hand, the measurement of density-time profiles in a shocked target using pulsed radiography is a difficult task, because it requires a high-intensity X-ray pulse of uniform amplitude, which cannot be realized with conventional methods of flash X-ray generation.
- ▶ Modern high-speed diagnostics also offer numerous indirect pressure measurement techniques. For example, British ballisticians used a calibrated time fuse in order to measure the pressure acting on the head of an actual 3.3-in. caliber shell shot by an 18-pdr. field gun that traveled at between Mach 0.9 and 1.2 – definitely an ingenious although unusual method of pressure measurement {BAIRSTOW ET AL. \Rightarrow 1920; \Rightarrow Fig. 4.6–M}.
- ▶ The U.S. shock researcher William C. HOLTON used water as a pressure gauge {M.A. COOK \Rightarrow 1962}. In order to measure detonation pressures in solid explosives, he coupled the detonation wave into a water tank with transparent windows and photographed the propagation of the shock wave at different moments in time – the so-called “aquarium technique.” Using the known Hugoniot data of water, he converted measured shock front propagation velocities into shock pressures.
- ▶ Physicists at the University of Stuttgart developed a needle hydrophone based on an optical fiber with an ultrashort rise time in order to measure compression pulses in water of up to +1,000 bar and rarefaction pulses of up to –100 bar {STAUDENRAUS & EISENMENGER \Rightarrow 1988}.

2.9 EVOLUTION OF COMPUTATIONAL ANALYSIS

*The question as to whether a solution which one has found by mathematical reason really occurs in nature and whether the existence of several solutions with certain good or bad features can be excluded beforehand, is a quite difficult and ambiguous one... Mathematically, one is in a continuous state of uncertainty, because the usual theorems of existence and uniqueness of a solution, that one would like to have, have never been demonstrated and are probably not true in their obvious forms... Thus there exists a wide variety of mathematical possibilities in fluid mechanics, with respect to permitting discontinuities, demanding a reasonable thermodynamic behavior etc., etc... It is difficult to say about any solution which has been derived, with any degree of assurance, that it is the one which must exist in nature.*³⁸²

John von NEUMANN
Institute for Advanced Study
Princeton, NJ 1949

FOR over half a century, the use of computer methods to study problems in almost all branches of science and engineering has grown in popularity. Such methods are used as both an aid to planning and interpreting experiments, and as a way to provide theoreticians with insights into the analysis of dynamic phenomena. The use of computers has caused numerical analysts to reconsider the classical methods associated with their research area. For example, the widespread application of computers has stimulated investigations into the basic computational problems of numerical stability, the relationship between the number of iterations required and the precision that must be carried through the calculation, as well as the relationship between the selected mesh size and the minimum time step required when simulating dynamic phenomena. Typically, shock waves and detonation waves in space are governed by nonlinear partial differential equations. One of the methods most frequently used to obtain approximate solutions to these is the *method of finite differences*, which essentially consists of replacing each partial derivative with a difference quotient. The digital computer has proved to be a very efficient tool for solving the resulting set of difference equations, and appropriate numerical codes such as the FDA (Finite Difference Approximation)

method were developed to solve partial differential equations. Today a wide spectrum of numerical codes for flow simulation purposes is readily available to the fluid dynamist {LANEY \Rightarrow 1998}.

During World War II, a quantum leap in the evolution of computational techniques was achieved in a few countries, including the United States, England and Germany; these were intended for use in military applications. In the United States, this development resulted in the first large-scale mechanical calculating machines, which were immediately applied to nuclear bomb physics. After the war, the development of high-speed electronic digital computers was mainly the result of urgent numerical analyses necessitated by the development of thermonuclear weapons, as well as numerical simulations of their new destructive effects – a consequence of the perceived Soviet threat to U.S. (and *vice versa*) during the long period of the Cold War (1945–1989). This placed heavy emphasis on research and development in ballistics, nuclear physics, detonics, aerodynamics, astronautics and related technical fields, such as high-speed photography and diagnostics, image processing, automatic control systems, lasers and pulsed power technology.³⁸³ In turn, this led to

- ▶ mounting interest in fast computation and in stored-program computers from universities and governmental and industrial research laboratories;
- ▶ the formation of professional groups concerned with computers;
- ▶ the staging of influential technical conferences;
- ▶ the foundation of computer science periodicals; and
- ▶ the creation of the Internet, which connects governmental institutions, companies, universities, corporate networks and hosts, thus providing quick and easy access to a huge number of different databases, which has tremendously enhanced communication among individual researchers.

According to a modern definition,³⁸⁴ *computers* are “electronic devices that are capable of accepting data and instructions, executing the instructions to process the data, and presenting the results.” The majority of historians also do not consider any machine to be a “computer” unless it embodies the stored-program concept. It may be interesting to note at

³⁸² J. VON NEUMANN: *Discussion of the existence and uniqueness or multiplicity of solutions of the aerodynamical equations*. Proc. of the Symposium on the Motion of Gaseous Masses of Cosmical Dimensions [Paris, France, Aug. 1949]. In: *Problems of cosmical aerodynamics*. Central Air Documents Office, Dayton, OH (1951), pp. 75-84.

³⁸³ F. HARLOW and N. METROPOLIS: *Computing and computers. Weapons simulation leads to the computer era*. Los Alamos Science **4**, 132-141 (1983).

³⁸⁴ C. MORRIS (ed.): *Dictionary of science and technology*. Academic Press, San Diego etc. (1992), p. 489.

this point that the term *computer* originally designated “a person employed to make calculations in an observatory, in surveying, etc.” – not a machine.³⁸⁵ It is not known with any certainty who first used the term *computer* to denote a calculating machine. Obviously, however, the modern term was not immediately accepted. For example, the 1961 edition of the *Britannica Encyclopaedia* still used the old-fashioned terms *calculating machine* and *computing machine* rather than the modern term *computer*.

The history of computing, which ranges from the first crude mechanical instruments to modern electronic computers, has been documented and discussed in a large number of books from technical, scientific, economic and human/social viewpoints;³⁸⁶ some of them, especially those written by distinguished computer pioneers, are particularly informative.³⁸⁷ In addition, a collection of essays³⁸⁸ on the history of computer technology, written by some of the foremost contributors in the field, provides first-hand information on a subject which for decades was covered by a veil of secrecy. Prominent examples include Arthur W. BURKS, J. Presper ECKERT, John W. MAUCHLY, Nicholas C. METROPOLIS, George R. STIBITZ, Stanislaus ULAM, Maurice V. WILKES and Konrad ZUSE – to name but a few of the 39 contributors to this collection of essays.

This chapter can only briefly review some of the most important milestones in the early era of the development of computers, and thus it attempts only to illustrate their close interrelations with the subject matter of this book. Obviously, during the pioneering era up to the end of World War II, the main impetus for developing faster and smaller electronic computers in Europe and the United States was almost exclusively the immediate solution of vital military problems such as those imposed by ballistics, fluid dynamics, shock wave physics and detonics – a stimulating process of complex interrelations which continued throughout the period of Cold War and right up to the present day.

2.9.1 THE PRE-COMPUTER ERA: TRIUMPH OF MECHANICAL AND GRAPHICAL METHODS

*The same thing which you have done by hand calculation, I have just recently tried to do in a mechanical way. I have constructed a machine which automatically reckons together the given numbers in a moment, adding, subtracting, multiplying and dividing.*³⁸⁹

Wilhelm SCHICKARD
Eberhard Karls Universität
Tübingen 1623

The two domains of *geometry* and *numbers* are the basis for and the essence of all mathematics. The development of calculating machines for providing such numbers was the main aim of generations of mathematicians, engineers and instrument-makers. The invention of infinitesimal calculus in the 17th century initiated rapid progress in formulating complex problems in fluid dynamics and ballistics via differential equations; however, their solution by analytical methods imposed great difficulties, and numerical approaches were beyond the abilities of the calculating machines that existed at that point. Geometry embraces far more than purely spatial concepts. In the 18th century, the eminent mathematicians Leonard EULER and Gaspard MONGE applied differential calculus to geometry in order to find solutions of differential equations by applying graphical procedures, thus creating differential geometry, the “modern language of physics.” Numerical and geometrical approaches to computation, which complement each other in a unique manner, are briefly discussed in the following.

Digital Mechanical Machines. The bead-and-wire *abacus*, invented in Egypt in around 500 B.C., is the oldest known example of arithmetic computational aid. The first significant steps toward the construction of mechanical computers were made as early as the 17th century by some distinguished natural philosophers. Wilhelm SCHICKARD, a German mathematician and orientalist, invented (before even PASCAL) the first *digital computing machine* (1623) that (according to his words): “...immediately computes the given numbers automatically; adds, subtracts, multiplies, and divides.” Unfortunately, his machine was destroyed in a fire shortly before his death. However, a few of his drawings survived and were

³⁸⁵ J.A. SIMPSON and E.S.C. WEINER: *The Oxford English dictionary*. Clarendon Press, Oxford, vol. III (1989), pp. 640–641.

³⁸⁶ See, for example M.R. WILLIAMS: *A history of computing technology*. IEEE Computer Society Press, Los Alamitos, CA (1997), pp 66–83.

³⁸⁷ M.V. WILKES: *Memoirs of a computer pioneer*. MIT Press, Cambridge, MA (1985); H.H. GOLDSTINE: *The computer. From PASCAL to VON NEUMANN*. Princeton University Press, NJ (1993); W.J. ECKERT and R. JONES: *Faster, faster: a description of a giant electronic calculator and the problems it solves*. McGraw-Hill Book Co., New York (1955); K. ZUSE: *The computer – my life*. Springer, Berlin (1993); and J. VON NEUMANN: *The computer and the brain*. Oxford University Press, London (1958).

³⁸⁸ N. METROPOLIS, J. HOWLETT, and G.C. ROTA (eds.): *A history of computing in the twentieth century*. Academic Press, New York etc. (1980).

³⁸⁹ From a letter to the German astronomer Johannes KEPLER (dated Sept. 20, 1623). In a later letter to KEPLER (dated Feb. 25, 1624), SCHICKARD enclosed a sketch of his calculating machine. Both letters have survived. See Wilhelm SCHICKARD: *Briefwechsel* (F. SECK, ed.). 2 vols., Frommann-Holzboog Verlag, Stuttgart (2002).

discovered in the 1950s in papers left by the German astronomer Johannes KEPLER, with whom he had corresponded. a working model reconstructed from his notes proved the soundness of his construction.³⁹⁰ In the early 1640s, Blaise PASCAL, a French philosopher, built a calculator to assist his father (a mathematician and judge who presided over the tax court) with local administration. Several arithmetic machines manufactured by him have survived. Gottfried W. LEIBNIZ, a German mathematician and philosopher, also constructed a calculating machine, a perfected version of an earlier machine developed by PASCAL, and presented it to the Royal Society in London (1673). His machine could add, subtract, multiply, divide, and extract roots.

Charles BABBAGE, an English mathematician and inventor, was the first to conceive of an automatic computer for mechanically calculating mathematical tables – the forerunner of the modern stored-program computer. However, his *analytical engine* (1833), which was designed to produce mathematical tables by accepting data and performing a sequence of different mathematical operations according to instructions from punched cards, was not completed. The U.S. statistician and inventor Herman HOLLERITH perfected the idea of punched cards from a technical standpoint and developed the *automatic tabulating machine* (1890) for use in statistics.

Eventually, these step-by-step improvements and inventions led to various kinds of mechanical and/or electromechanical *hand calculators* and *punched-card machines* for adding, subtracting, multiplying and dividing two numbers, which found wide application in science, commerce and statistics.

In 1928, the first important scientific application of HOLLERITH's punched-card technique was demonstrated by Leslie John COMRIE, an astronomer and pioneer in mechanical computation from New Zealand. He succeeded in numerically solving the classical “three-body problem” of Newtonian celestial mechanics (the gravitational interaction of the masses of Sun, Earth and Moon), a surprisingly difficult mathematical task which had previously frustrated not only such eminent mathematicians as D’ALEMBERT, EULER, DE LAGRANGE and DE LAPLACE, but also subsequent generations of astronomers.³⁹¹ Using the *Hollerith tabulator*, an 80-column punched card machine from IBM, he calculated lunar orbits. COMRIE's method of applying punched-card com-

putation to astronomy was picked up in the United States by Wallace J. ECKERT, an astronomer by training and a computer engineer at Columbia University, who became one of America's leading proponents of punched-card computation in the 1930s.

During World War II, theoretical physicists at Los Alamos, who were facing problems that were insoluble by analytical means and were also far too complicated to be solved by desk computing machines, reviewed ECKERT's successful application and adapted his computing method to their own needs, decisively stimulating the further development of such machines in the United States (*see below*).

Analog Mechanical Machines. The idea of the *slide rule* (1614) rests upon the idea of logarithms formulated by the Scottish mathematician John NAPIER, who also built a primitive calculating machine that used calculating rods to quickly multiply, divide and extract roots. His mechanical numbering device was made of horn, bone or ivory, later known as “Napier bones.” Around 1620 the English mathematician William OUGHTRED came up with the idea of using a circular slide rule to improve accuracy. The standard rectangular slide rule, based upon a construction devised by the French military officer Amédée MANNHEIM (1859), was in common use until the early 1970s. The *planimeter* (1814), which was also an analog instrument, was devised by the Bavarian engineer Johann H. HERMANN to measure the value of a definite integral provided graphically as a planar surface, by tracing its boundary lines.

William THOMSON (later Lord KELVIN) and his brother James THOMSON, an engineering professor at the University of Glasgow, devised the *differential analyzer* (1876), one of the earliest mechanical analog computers capable of solving differential equations, which they used to calculate tide tables. In the late 1920s, the U.S. engineer Vannevar BUSH and his colleagues at MIT developed the *network analyzer*, a system for setting up miniature versions of large and important electrical networks. At the same time, they developed a prototype of the differential analyzer, the first analog computer capable of solving integral equations. BUSH suggested its application to solve numerical problems of linear and nonlinear electrical networks. During World War II, he worked on radar antenna profiles and calculated artillery firing tables.

The differential analyzer was later also extended to solve ordinary second-order differential equations. In the early 1930s, the Mexican-born U.S. scientist Manuel Sandoval VALLARTA and the Belgian mathematician and abbot Georges LEMAÎTRE { \Rightarrow 1927}, cocreator of the Big Bang Model

³⁹⁰ B. VON FREYTAG LÖRINGHOFF: *Über die erste Rechenmaschine*. Physik. Blätter **14**, 361-365 (1958); *Wiederentdeckung und Rekonstruktion der ältesten neuzeitlichen Rechenmaschine*. VDI-Nachrichten **14**, Nr. 39, 4 (1960).

³⁹¹ E.O. LOVETT: *The problem of several bodies: recent progress in its solution*. Science **29**, 81-91 (Jan. 15, 1909).

for the evolution of the Universe, used BUSH's machine in their complex calculations on the distribution of primary cosmic radiation.

The ability to solve ordinary differential equations is also highly relevant to exterior ballistics. Here the main task is to describe, for a given fuse/shell/gun combination, the position and velocity of the projectile when the gun is fired at various elevations and initial velocities. The problem becomes even more complex when aiming at a moving target from a mobile position. In 1935, the German Siemens AG built C35, the "Artillerie-Schußwert-Rechner" which was installed on the battleships *Gneisenau* and *Scharnhorst* for guiding surface-to-air missiles (SAMs). The roughly 1-ton mechanical device contained about 2,000 gear-wheels.³⁹² An analog computer was also used in the German V2 rocket for guidance purposes.

In World War II, the requirements of anti-aircraft artillery "predictors," a particularly challenging task, stimulated activities aimed at improving existing analog computers. In these, the variables were the latitude, longitude, and height of the target and those of the projectile, respectively, all of which varied rapidly with time. The input data were the muzzle velocity, the ballistic characteristics of the projectile and atmospheric conditions like the wind velocity and air density. The analog computer had to solve two simultaneous equations so that the target and the projectile, each of which was moving along its own course, would arrive at the point of intersection at the same time. In 1940, Clarence A. LOVELL and David B. PARKINSON at Bell Telephone Laboratories developed an analog computer that could be used to control aircraft guns. Two years later, they built the M-9 GUN PREDICTOR, another "ballistic computer" for predicting the future position of an aircraft (based on its precise current position, its course and its speed) and firing data for an anti-aircraft gun. This more advanced analog device, which used a set of wheels to set potentiometer resistances, accepted electrical inputs from the XT-1, a truck-mounted microwave radar, and sent electrical outputs to the anti-aircraft guns to direct them accordingly. One radar and one M-9 could control a battery of four guns. In 1941, at the Peenemünde Rocket Center the German electrical engineer Helmut HOELZER³⁹³ developed an electronic circuit with phase-shifting elements that could integrate differential equations – the first fully electronic general-purpose analog computer –

which was applied to the guidance system of the A-4, the world's first long-range ballistic missile {HVA Peenemünde ⇒ 1942}.

Another application of analog computers was to aerodynamics, where they were particularly useful for solving equations relating lift to air flow characteristics, yaw angle and airfoil geometry. The British physicist and mathematician Douglas R. HARTREE³⁹⁴ developed the *differential analyzer*, an analog computer. He first proposed its use to solve partial differential equations – particularly of the hyperbolic type, which are of the greatest importance in fluid dynamics – and in 1955 he eventually fabricated such a mechanical device. He succeeded in solving parabolic partial differential equations, but after also attempting to treat the hyperbolic type, he had to admit that "a few attempts have been made to apply it to equations of hyperbolic type, with only partial success." His attempts were too ambitious for his time and this problem was not successfully solved until the advent of digital calculating machines.

Some stages in the unique history of mechanical analog computers used to control the firing of large guns, ranging from early developments up to their golden age in World War II and their subsequent obsolescence in the 1950s, have been reviewed fairly recently.³⁹⁵

Graphical Concepts. In addition to numerical analysis, various graphical methods were used. High-speed flows are termed *hyperbolic* and can be solved graphically. This *method of characteristics* {MONGE ⇒ 1770; PRANDTL & BUSEMANN ⇒ 1929} was used in unsteady gas dynamics to solve 1-D and 2-D fluid dynamic problems, e.g.:

- ▶ to solve the "Lagrange problem" in ballistics {DE LAGRANGE ⇒ 1793};
- ▶ to shape the geometries of Laval nozzles in supersonic wind tunnels {PRANDTL 1906; WIESELSBERGER & HERMANN ⇒ 1934};
- ▶ to analyze the operating cycle of the pulse-jet engine invented by the German engineer Paul SCHMIDT {⇒ 1930}, the "Schmidt tube" (P. SCHMIDT ⇒ 1930; BUSEMANN 1936 and SCHULTZ-GRUNOW 1943, see Sect. 5);
- ▶ to describe the propagation of spherical blast waves (SCHULTZ-GRUNOW 1943);
- ▶ to determine the lateral expansion of the gases behind a detonating slab of explosive {HILL & PACK ⇒ 1947};

³⁹² H. PETZOLD: *Moderne Rechenkünster*. Beck, München (1992).

³⁹³ H. HOELZER: *Anwendung elektrischer Netzwerke zur Lösung von Differentialgleichungen und zur Stabilisierung von Regelvorgängen (gezeigt an der Stabilisierung des Fluges einer selbst- bzw. ferngesteuerten Großrakete)*. Ph.D. thesis, TH Darmstadt (1946).

³⁹⁴ D.R. HARTREE: *Calculating instruments and machines*. University of Illinois Press, Urbana, IL (1950), pp. 33-34.

³⁹⁵ A. BEN CLYMER: *The mechanical analog computers of Hannibal FORD and William NEWELL*. IEEE Ann. Hist. Comput. 15, No. 2, 19-34 (1993).

- ▶ to solve various problems in hydrodynamics {OSWATITSCH \Rightarrow 1947}
- ▶ to determine the flow in a steady supersonic jet of air issuing from a slightly supersonic circular orifice into a vacuum {OWEN & THORNHILL \Rightarrow 1948}; and
- ▶ to treat steady 2-D and 3-D flows with shock waves (FERRI 1954).

In hydrodynamics, the *LÖWY-SCHNYDER method* {BERGERON \Rightarrow 1937} was used to calculate the propagation and reflection of hydrodynamic shocks in water supply lines. Such shocks (the *water hammer effect* {CARRÉ \Rightarrow 1705; ZHUKOVSKY \Rightarrow 1898}) can cause damage to pipes in hydraulic installations.

2.9.2 REVOLUTION IN CALCULATION: THE AUTOMATIC DIGITAL COMPUTER

*The ENIAC project was funded to facilitate the preparation of firing tables. The calculation of trajectories was a good problem for computing machines, because the calculation depends critically on the drag function $G(v^2)$, which gives the resistance of the air to the movement of the shell as a function of the velocity squared. This function is an ill-behaved function of the shell's velocity, especially as the shell passes through the sound barrier. In hand calculation the resistance was read from printed tables, and on the differential analyzer the resistance was fed in from an input table... All of these table-input methods were too slow for ENIAC. Hence, we used variable resistor matrices set by hand switches...*³⁹⁶

Arthur W. BURKS
University of Michigan
Ann Arbor, MI 1980

Digital Electromechanical Computers. While studying magnetomechanics of telephone relays, the U.S. applied mathematician George R. STIBITZ turned his attention in 1937 to relay-controlled binary circuits. In the following year, with the support of Bell Laboratories in New Jersey, he developed a *two-digit binary adder*, which was operational late in 1939 and was demonstrated in 1940 by remote control between several U.S. cities. During the war he designed various circuits and supervised the design of a *relay interpolator* and a *relay ballistic computer* (named the “Stibitz Computer”) for the National Defense Council (NDC).

Today STIBITZ is internationally recognized as being the father of the modern digital computer. However, in Germany, the engineer Konrad ZUSE also independently created a binary calculator that he named ZUSE 1 (or Z1). This was the first *binary digital computer*, and it became operational as a test model in 1938, one year prior to STIBITZ’s calculator. During World War II, financially supported by the Reichsluftfahrtministerium (German Ministry of Aerial Warfare), he built several special relay-based machines for the Henschel Flugzeugwerke AG Berlin, which were immediately applied to aerodynamic calculations of the Hs 293, a radio-guided winged bomb provided with a rocket engine.³⁹⁷ In the period 1942–1945, he designed his Z4, a fully programmable computer which became operational in the beginning of 1945, for the Aerodynamische Versuchsanstalt (AVA) at Göttingen. His instrument, which was renovated and supplemented after the war, was initially operated at the Institute for Applied Mathematics of the ETH Zurich (1950–1955). It was programmed by the Swiss applied mathematician Heinz RUTISHAUSER, one of the founders of ALGOL (1958–1960). The calculating machine was then moved to France, to the Laboratoire de Recherches Techniques de Saint-Louis { \Rightarrow 1945}, where it was used for defense work until 1960. a reconstruction of ZUSE’s computer Z3 (operational in 1941, destroyed during the war) and his original Z4 (operational at the end of war) are now on permanent display at the exhibition “Informatik” of the Deutsches Museum in Munich.

The first *automatic digital computer* was conceived by Howard H. AIKEN of Harvard University (Cambridge, MA). Planned long before the war, and built in cooperation with the IBM Corporation,³⁹⁸ this large-scale, relay-based punched-card machine was not completed until 1944, when it was installed at Harvard University. Named ASCC (Automatic Sequence Controlled Calculator), or MARK I, it was mostly an electromechanical device, a “relay calculator” that was capable of performing only about three additions per second, and it was primarily used for computing ballistic data. a second machine, MARK II, was built in 1944 for the Naval Proving Ground Group (Dahlgren, VA) in order to provide vital ballistic calculations. Both the MARK I and MARK II were decimal machines, and operations – not yet programs in the modern sense – could be tailored to a specific application by inserting “plugwires” into a “plugboard.”

³⁹⁶ BURKS was one of the leading pioneers in his field. He developed and built ENIAC, the world’s first electronic, digital, general-purpose scientific computer, at the Moore School of Electrical Engineering, University of Pennsylvania. See his article *From ENIAC to the stored-program computer: two revolutions in computers*. In: (N. METROPOLIS ET AL., eds.): *A history of computing in the 20th century*. Academic Press, New York etc. (1980), pp 311-344.

³⁹⁷ K. ZUSE: *Der Computer – mein Lebenswerk*. Springer, Berlin etc. (1984), pp. 62-64.

³⁹⁸ C.J. BASHE, L.R. JOHNSON, J.H. PALMER, and E.W. PUGH: *IBM’s early computers*. MIT Press, Cambridge, MA (1986), pp. 25-33.

The new computing machines were mostly used to solve problems encountered in the development of the first atomic bomb, for example:

- ▶ to calculate the neutron diffusion for a sphere of fissionable material surrounded by a spherical shell of inert, scattering material;
- ▶ in the development of an equation of state (EOS) for uranium and plutonium by interpolating between high-pressure data obtained by numerically solving the Thomas-Fermi differential equation and low-pressure data obtained experimentally;
- ▶ in hydrodynamic calculations, particularly when calculating the propagation of shock waves and compression in the spherically symmetric implosion of the Trinity atomic bomb (VON NEUMANN & NEDDERMEYER 1943); and
- ▶ to solve the three-shock problem or Mach reflection {VON NEUMANN \Rightarrow 1943}, which was of immediate interest for determining the “optimum” height of burst (VON NEUMANN, Sept. 1944) in the planned bombing of Hiroshima and Nagasaki.

In 1944, the Los Alamos Scientific Laboratory (LASL) ordered ten IBM machines in order to help calculate the critical masses of odd-shaped bodies and to solve hydrodynamic equations for implosion. These IBM machines could not be programmed, and a considerable number of intermediate steps had to be done by hand. Hans A. BETHE,³⁹⁹ head of the Theoretical Division at Los Alamos during World War II, remembered, “In our wartime calculations, the Hugoniot conditions at the shock front were fitted by hand, at each time step in the calculation. The position of the shock front was also calculated by hand, using the shock velocity deduced from the Hugoniot equation at the previous time step. This was a somewhat laborious procedure; but each time step on the computer took about one hour, so that the hand calculations could easily keep in step with the machine.”

The U.S. mathematician and computer pioneer Herman H. GOLDSTINE,⁴⁰⁰ who became a major contributor to the logical design of the EDVAC (*see below*), and who cooperated with John VON NEUMANN on various numerical analysis projects, remembered that “the main motivation for the first electronic computer was the automation of the process of producing firing and bombing tables.” GOLDSTINE, who headed a section of the Ballistic Research Laboratory (BRL)

at the Moore School of Electrical Engineering of the University of Pennsylvania in 1942, was himself engaged in generating new calculating instruments for the faster production of such shooting tables.

Digital Electronic Computers. The first electronic digital computer was named the ENIAC (Electronic Numerical Integrator and Calculator), a large programmable digital machine initially designed to recompute artillery firing and bombing tables for the Ordnance Corps of the U.S. Army. It was built primarily to integrate the equations of external ballistics in a step-by-step process, but it was flexible enough to be applied to a wide range of large-scale computations other than the numerical integration of differential equations.⁴⁰¹

The ENIAC was developed by John W. MAUCHLY, a professor of electrical engineering, and J. Presper ECKERT, a young electronic engineer. Both worked at the Moore School of Electrical Engineering at the University of Pennsylvania, which was a center for calculating firing tables and trajectories at that time. In August 1942, MAUCHLY wrote a memo entitled *The Use of High Speed Vacuum Tube Devices for Calculating* in which he proposed the idea that the speed of calculation “can be made very much higher than of any mechanical device.” VON NEUMANN and ECKERT proposed to achieve a high computing speed by operating vacuum-tube circuits at 100,000 pulses per second – *i.e.*, using pulses at 10 μ s intervals – which was indeed realized with the final version of the ENIAC. This computing machine became operational in 1946 at the Moore School and in 1947 at the Ballistic Research Laboratory (BRL) in Aberdeen Proving Ground, MD.⁴⁰² The 30-ton ENIAC contained about 18,000 electron tubes and 70,000 resistors, and used punched cards for input and output data. It was more than 1,000 times faster than its electromechanical predecessors and could execute up to 5,000 additions per second.

The ENIAC was designed primarily for use in exterior ballistics, particularly for the step-by-step integration of differential equations in order to calculate ballistic trajectories of bombs and shells. However, from the beginning, ECKERT’s goal was to make it generally useful for other military problems too, such as those in interior ballistics and for all kinds of data reduction. In the period from December 1945 to January 1946, VON NEUMANN used the ENIAC at Los Alamos for a pre-

³⁹⁹ H.A. BETHE: *Introduction*. In: (S. FERNBACH and A. TAUB, eds.): *Computers and their role in the physical sciences*. Gordon & Breach, New York etc. (1970), pp. 1-9.

⁴⁰⁰ H.H. GOLDSTINE: *The computer. From PASCAL to VON NEUMANN*. Princeton University Press, NJ (1993), p. 135.

⁴⁰¹ K. KEMPF: *Electronic computers within the ordnance corps*. Historical monograph covering the pioneer efforts and subsequent contributions of the U.S. Army Ordnance Corps in the field of automatic electronic computing systems during the period 1942–1961; <http://ftp.arl.mil/~mike/comphist/61ordnance/>.

⁴⁰² W.T. MOYE: *ENIAC: The army-sponsored revolution*. ARL (Jan. 1996); <http://ftp.arl.mil/~mike/comphist/96summary/index.html>.

liminary study on the hydrogen bomb, Edward TELLER's planned thermonuclear "super bomb." This challenging task amounted to solving a system of partial differential equations. However, it turned out that the "super problem" was too complicated for the ENIAC with its 1,000 bits of memory, and only a highly simplified version of the calculation was run, which revealed very little about how such a weapon might work.⁴⁰³ In September 1946, Abraham H. TAUB, a mathematician and theoretical physicist at Princeton University, used the ENIAC to calculate reflection and refraction phenomena of shock waves {BLEAKNEY \Rightarrow 1946}. In the same year, the machine was moved to BRL, which was in the process of becoming one of the great wartime and postwar computing centers in the United States. An informative collection of review papers on the development of ENIAC and early computer applications at BRL was published in 1996.^{404, 405}

By March 1945, VON NEUMANN had begun to consider a computer that was not assigned to definite, often very specialized (military) purposes, but was instead allowed to run quite freely and be governed by scientific considerations. In particular, he had in mind a new computing device powerful enough to solve nonlinear partial differential equations with two or three independent variables, such as those used for weather prediction and in the study of the properties of numbers. Indeed, VON NEUMANN proposed that this planned computer, dubbed EDVAC (Electronic Discrete Variable Automatic Computer), should be a *stored-program serial computer*; this architectural design was used in several subsequent generations of computers.⁴⁰⁶ He described his concept in a paper entitled *First Draft of a Report on the EDVAC*, written in the spring of 1945 for the U.S. Army Ordnance. A "program" is a sequence of instructions on how to perform particular operations on data contained in a memory. His stored-program concept, the so-called "von Neumann

architecture," translated mathematical procedures into a machine language of instructions. The "von Neumann machine" was characterized by a large Random Access Memory (RAM) that was used to address memory locations directly, and a Central Processing Unit (CPU) that possessed a special working memory.

VON NEUMANN also devised a method for converting the relay-based ENIAC concept of an externally programmed machine into that used by EDVAC. The plugboards and programming switches of the ENIAC were replaced in the EDVAC by an electrically alterable memory that could store both the instructions and numbers to be used in a calculation at electronic speeds. The EDVAC was built by the U.S. National Bureau of Standards and operated by the Ballistic Research Laboratory at Aberdeen from 1950 onwards. EDVAC was the first American stored-program computer. Prior to this, however, the first computer to meet the criterion of VON NEUMANN's stored-program concept was the EDSAC (Electronic Delay Storage Automatic Calculator), which performed its first calculations in May 1949. This binary, serial-type computer, which was the first to use supersonic delay lines for memory,⁴⁰⁷ was built in Great Britain by Maurice V. WILKES⁴⁰⁸ and his team at the Mathematical Laboratory of Cambridge University, later known as the "Computer Laboratory." In 1945, a number of British visitors came to the Moore School, and these visits prompted the computerization of Great Britain, which also resulted in the MADM (Manchester Automatic Digital Machine) at the University of Manchester and the ACE (Automatic Computing Engine) at NPL in Teddington.

The first generation of *stored-program computers* also included the IAS, a computer built at the Institute for Advanced Study (IAS) at Princeton University; the early real-time WHIRLWIND designed under the leadership of Jay FORRESTER at MIT's Digital Computer Laboratory; the UNIVAC I (Universal Automatic Computer) at the Moore School of the University of Pennsylvania; and many others. The UNIVAC I, designed by ECKERT and MAUCHLY, was the first general-purpose computer to be made commercially available – before this, computers had only been rented and had to be constantly serviced and often required repairs. Nicholas C. METROPOLIS and associates at Los Alamos built the MANIAC (Mathematical Analyzer, Numerical Integrator and Computer), which began operation in March 1952. The MANIAC,

⁴⁰³ A. FITZPATRICK: *TELLER's technical nemesis: the American hydrogen bomb and its development within a technological infrastructure*. Phil Tech 3, No. 3, 10-17 (1998).

⁴⁰⁴ M.H. WEIK: *The ENIAC story*. Ordnance [A journal of the American Ordnance Assoc., Washington, DC] (Jan./Feb. 1961); <http://ftp.arl.mil/~mike/comphist/eniac-story.html>.

⁴⁰⁵ See (T.J. BERGIN, ed.) *50 years of army computing. From ENIAC to MSRC*. Record of a symposium and celebration, Aberdeen Proving Ground, MD (Nov. 13-14, 1996). Rept. ARL-SR-93, Army Research Laboratory (ARL), Aberdeen Proving Ground, MD (Sept. 2000); <http://stinet.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA431730>.

⁴⁰⁶ In the mid-1930s, the German engineer Konrad ZUSE developed a concept which closely approached VON NEUMANN's idea of a program stored in the memory of a calculating machine. In 1936, ZUSE applied for a German patent, which, however, he did not get; see K. ZUSE: *Verfahren zur selbst-tätigen Durchführung von Rechnungen mit Hilfe von Rechenmaschinen*. Dt. Patentanmeldung Z 23139/GMD Nr. 005/021 (1936).

⁴⁰⁷ The EDVAC used supersonic (meaning here ultrasonic) delay lines – acoustic high-speed internal memories consisting of mercury-filled tubes about 5' long and 1" in diameter in contact with a quartz crystal at each end.

⁴⁰⁸ M.V. WILKES: *Memoirs of a computer pioneer*. MIT Press, Cambridge, MA (1985).

like the EDVAC and the IAS, was also used for calculations related to the development of the first hydrogen bomb {MIKE Test \Rightarrow 1952}.

In the Soviet Union, work on the development of computers had begun in 1947 in order to use this new technology in the fields of nuclear physics, reactor technology, ballistics, electronics, gas dynamics, *etc.* Several different computers were developed in the 1950s. The most important of these was the BESM (*Bolshaja Elektronno-Schetnaja Mashina*, meaning “Large Electronic-Computing Machine”), which was designed under the leadership of Sergei Alexeevich LEBEDEV and set in operation in 1952. Employing about 5,000 vacuum tubes and a William-tube memory, it was then Europe’s fastest computer and it closely matched the American IBM 701 (introduced in 1954) in terms of performance. One of the first uses for Russian computers was to perform calculations related to the development of the first Soviet thermonuclear bomb {Semipalatinsk Test Site \Rightarrow 1955}.⁴⁰⁹ In the 1950s, further Russian digital computers were designed and built, for example STRELA (1953), a large William-tube machine; URAL (1955), a magnetic drum computer; and others. Herman H. GOLDSTINE⁴¹⁰ provided a general survey of worldwide computer development, also including the Soviet Union.

2.9.3 THE TRICKY PROBLEM: TREATING FLOW DISCONTINUITIES NUMERICALLY

*In the investigation of phenomena arising in the flow of a compressible fluid, it is frequently desirable to solve the equations of fluid motion by stepwise numerical procedures, but the work is usually severely complicated by the presence of shocks. The shocks manifest themselves mathematically as surfaces on which density, fluid velocity, temperature, entropy and the like have discontinuities.*⁴¹¹

John VON NEUMANN
Robert D. RICHTMYER
Institute for Advanced Study
Princeton, NJ 1950

In the pioneering era of shock wave research, digital computers proved very useful for solving problems involving continuous quantities; *i.e.*, those that change smoothly rather

than “jump,” like the thermodynamic quantities at a shock front. Many problems relevant to the military, however, were related to supersonic flow and detonation, like the propagation and reflection of a blast wave originating from a strong (nuclear) explosion. This immediately raised the problem of how to treat wave discontinuities numerically. In particular, the problem of simulating implosions became crucial to the planned design for the implosion bomb during 1943 and 1944, and this required the integration of hyperbolic partial differential equations and the use of realistic high-pressure equations of state for the high explosive, the uranium tamper and the plutonium core. This was a very difficult and complex task that could not be done by hand. In addition, plutonium was only available in very small quantities at that time, and experimentally obtained equation-of-state data were not yet available. Other important applications of digital computers included those to computational aerodynamics, particularly in the design of so-called “shock-free” configurations for transonic flight – a speed regime that all high-speed tactical aircraft were still confined to during World War II.

The first hydrodynamic initial value problems with prescribed boundary conditions that were fed into a computer were one-dimensional, and so the *Lagrangian* coordinates – *i.e.*, fixed-in-the-material coordinates – were most appropriate. The first two-dimensional codes were also in Lagrangian coordinates, but instability problems were encountered when treating discontinuities like shock waves. These were not understood until VON NEUMANN’s rediscovery of a pre-World War II paper on approximation mathematics {COURANT, FRIEDRICHS & LÉWY \Rightarrow 1928}, in which a condition for stability in the solution of partial differential equations was worked out; this was later called by VON NEUMANN the “Courant criterion.” However, in the early days of computers, there were two limiting factors which rendered numerical fluid dynamics difficult: the limited memory available to store the data for the cells, and the computer time required to process the solution to completion.

VON NEUMANN was the first to attempt to apply digital computers to solve true shock wave problems, at the Institute for Advanced Study at Princeton University. According to William ASPRAY,⁴¹² a notable computer historian, VON NEUMANN developed three of the earliest numerical approaches for treating shock waves. Following ASPRAY’s view, his methods were these:

⁴⁰⁹ D. HOLLOWAY: *STALIN and the bomb*. Yale University Press, New Haven, CT & London (1994), p. 314.

⁴¹⁰ H.H. GOLDSTINE: *The computer from PASCAL to VON NEUMANN*. Princeton University Press, Princeton (1972), pp. 349-362.

⁴¹¹ J. VON NEUMANN and R.D. RICHTMYER: *A method for the numerical calculation of hydrodynamic shocks*. J. Appl. Phys. **21**, 232-237 (1950).

⁴¹² W. ASPRAY: *John VON NEUMANN and the origins of modern computing*. MIT Press, Cambridge, MA (1992), pp. 108-110, 112, 288.

His oldest attempt to treat shock discontinuities goes back to a report published in 1944.⁴¹³ He proposed replacing the full hydrodynamic phenomena with a simple kinetic model that simulated the fluid using a line of beads connected by springs, a simple model for simulating continuum mechanics that DE LAGRANGE { \Rightarrow 1788} had already proposed in his *Mécanique analytique*. In this one-dimensional shock wave model { \Rightarrow Fig. 4.4–D} – previously also proposed by Charles V. BURTON (1893) in England and later picked up by Lev V. AL'TSHULER (1965) in the former Soviet Union – the beads represent the idealized molecules and the springs the inter-molecular forces. ASPRAY wrote, “VON NEUMANN was convinced that 14 bead molecules would be satisfactory for shocks in one dimension but that as many as 3,000 beads may be required in two- and three-dimensional problems which would probably have placed the problem beyond the range of calculating equipment then available.” In order to calculate a similar collision problem imposed by the development of nuclear weapons using the ENIAC, VON NEUMANN suggested his Monte Carlo method (1946–1947), which he worked out together with the Polish-born U.S. mathematician Stanislaus ULAM. He proposed to calculate the actions of 100 neutrons throughout the course of 100 collisions each in order to trace the isotropic generation of neutrons from a variable composition of active material along the sphere radius.

His second approach was developed in collaboration with the Los Alamos physicist Robert D. RICHTMYER. They introduced an artificial viscosity into numerical calculations to “smear out the discontinuity” such that the shock thickness becomes larger than the spacing on the grid points. The difference equations could then be solved directly, as if there were no shocks {VON NEUMANN & RICHTMYER \Rightarrow 1950}.

His third approach to the shock problem, undertaken in collaboration with the U.S. computer expert Hermann H. GOLDSTINE, was a direct numerical assault, one of the first attempts to solve a complex problem involving shocks directly by numerical means.⁴¹⁴ Considering the delay and propagation of a shock wave from a strong point-source explosion in an ideal gas, they applied an iterative method to calculate the Rankine-Hugoniot conditions {HUGONIOT \Rightarrow 1887} across the shock.

Retrospectively, the second method of simulating shock waves, where an artificial viscosity was added to the hydro-

dynamic equations, became the most important method of treating flow discontinuities numerically. Early computers, however, barely had enough capacity to solve 2-D shock problems with sufficient resolution in time and space, and the numerical treatment of true three-dimensional shock problems was still far beyond them.

The enormous computational resources at Los Alamos, Livermore and Albuquerque (Sandia), which were provided for programs of national interest, particularly the development of nuclear weapons, were most useful for analyzing materials under high shock compression, which stimulated the evolution of *Computational Fluid Dynamics (CFD)*, an entirely new discipline creating a wealth of new numerical simulation techniques.⁴¹⁵ Early codes for solving shock wave problems in solids were called “hydrocodes,” because the deviatoric stresses – stresses that cause the volume to deviate from its original proportions – were neglected, an assumption typically made for fluids. Originally, hydrocodes were developed for modeling fluid flow at all speeds, but they also proved useful to study natural high-dynamic events (such as the hypervelocity impact of an asteroid on a planet) which are complex enough that an analytical solution is not possible.⁴¹⁶

Ideally, a computer simulation should apply an appropriate algorithm, generally called a “numerical method,” to produce sharp approximations to discontinuous solutions automatically; *i.e.*, without explicit tracking and the use of jump conditions. Methods that attempt to do this are called “shock-capturing methods,” a number of numerical methods that use conservation laws to solve Euler and Navier-Stokes equations have been available for at least ten years now.⁴¹⁷ A recent review of numerical methods was given by Philip L. ROE,⁴¹⁸ a renowned numerical fluid dynamicist at the Dept. of Aerospace Engineering at the University of Michigan.

An increasing number of commercial numerical codes for treating shock discontinuities have been made available. However, comparisons of the codes with each other and with experimental results provide the crucial test in this case, and VON NEUMANN’s previous reflections on this problem, on whether an obtained solution really occurs in nature – see the citation provided at the start of this section – is still the fundamental question. In this way, Kazuyoshi

⁴¹³ J. VON NEUMANN: *Proposal and analysis of a numerical method for the treatment of hydrodynamical shock problems*. Rept. 108.1R AMG-IAS No. 1, Applied Mathematics Group, Institute for Advanced Study, Princeton, NJ (1944).

⁴¹⁴ H. GOLDSTINE and J. VON NEUMANN: *Blast wave calculation*. Commun. Pure Appl. Math. **8**, 327-353 (1955).

⁴¹⁵ N.L. JOHNSON: *The legacy and future of CFD at Los Alamos*. Rept. LA-UR-96-1426, LANL, Los Alamos, NM (1996).

⁴¹⁶ W.E. JOHNSON and C.E. ANDERSON: *History and application of hydrocodes in hypervelocity impact*. Int. J. Impact Engng. **5**, 423-439 (1987).

⁴¹⁷ R.J. LEVEQUE: *Numerical methods for conservation laws*. Birkhäuser, Basel etc. (1992).

⁴¹⁸ P.L. ROE: *Numerical methods*. In: (G. BEN-DOR ET AL., eds.) *Handbook of shock waves*. Academic Press, New York, vol. 1 (2001), pp. 787-876.

TAKAYAMA,⁴¹⁹ a shock physics professor at the Shock Wave Research Center of Tohoku University in Sendai, initiated an interesting comparison test in 1997 by calculating the Mach reflection of a shock wave that propagates at Mach 2 in air and strikes a 46°- and a 49°-wedge on a computer. This unique international benchmark test, so far supported by eighteen numerical contributions (using different numerical methods) and three experimental contributions (using contact shadowgraphy and holographic interferometry), has shown that the structures of shock waves passing over wedges – a rather difficult problem that has occupied shock physicists for almost fifty years – can indeed successfully be captured by present numerical techniques.

In astrophysics, numerical hydrodynamic simulations have become an indispensable tool for linking observations with theory, thus promoting the understanding of many astrophysical flow phenomena such as shock wave formation in core collapse supernovae and astrophysical jets. Such objects are not accessible to any kind of experimental manipulation, so astrophysicists must rely solely on information they can receive from astrophysical phenomena via electromagnetic radiation (e.g., from radio, Roentgen or optical telescopes), measured particle radiation (e.g., cosmic rays), and magnetic fields. The situation is further complicated by three facts:⁴²⁰

- ▶ the physical processes that give rise to the astrophysical phenomena may occur deep inside the observed object and are inaccessible to observation;
- ▶ these processes may involve extreme conditions which are experimentally inaccessible in the laboratory; and
- ▶ such processes often occur on timescales that are much longer than a human life span; i.e., one obtains only a snapshot of the phenomena.

Since the mid-1990s, supercomputers have increasingly been used worldwide to numerically simulate complex 3-D physical phenomena in climate research, materials science and nuclear weapons development. One particular challenge is to investigate events in astrophysics and cosmology using numerical simulation methods, such as the collisions of asteroids and planets, supernova explosions and gamma-ray bursts, collisions of two neutron stars, galaxy and quasar formation, galaxy-galaxy collisions, and convection and magnetic-field generation in the fluid interiors of planets and stars.

In 2003, on the occasion of the 50-year anniversary of coining the term *computer experiment*, Steven STROGATZ,⁴²¹ a professor in the Department of Theoretical and Applied Mechanics at Cornell University, wrote in *The New York Times*: “In 1953, Enrico FERMI and two of his colleagues at Los Alamos Scientific Laboratory, Jon PASTA and Stanislaw M. ULAM, invented the concept of a ‘computer experiment.’ Suddenly the computer became a telescope for the mind, a way of exploring inaccessible processes like the collision of black holes or the frenzied dance of subatomic particles – phenomena that are too large or too fast to be visualized by traditional experiments, and too complex to be handled by pencil-and-paper mathematics. The computer experiment offered a third way of doing science. Over the past 50 years, it has helped scientists to see the invisible and imagine the inconceivable... But perhaps the most important lesson of FERMI’s study is how feeble even the best minds are at grasping the dynamics of large, nonlinear systems. Faced with a thicket of interlocking feedback loops, where everything affects everything else, our familiar way of thinking fall apart. To solve the most important problems of our time, we’re going to have to change the way we do science.”

2.10 CONCLUDING REMARKS

*Scientists in the shock wave field are becoming too closely programmed. There is a feeling among productive scientists that a minute in which progress is not made toward some programmed objective is a minute wasted... This philosophy produces a lot of data and a lot of papers, but it has some negative aspects. It deprives the scientist of the perspective required to evaluate what he’s doing. It encourages the scientist to go on doing what he has done in the past for too long because study and thought take time. The net result may be a net loss to science... It is dangerous to proceed far without tapping the knowledge of the scientists in the laboratory.*⁴²²

George E. DUVALL
Washington State University
Pullman, WA 1985

RETROSPECTIVELY, the evolution of percussion, explosion and shock wave research as illustrated here in a rather condensed form has taken such a bizarre and complex

⁴¹⁹ K. TAKAYAMA: *Shock wave reflection over wedges: a benchmark test for CFD and experiments*. Shock Waves 7, 191-203 (1997).

⁴²⁰ E. MÜLLER: *Simulation of astrophysical fluid flow*. In: (R.J. LEVEQUE and O. STEINER, eds.) *Computational methods for astrophysical fluid flow*. Springer, Berlin (1998).

⁴²¹ S. STROGATZ: *The real scientific hero of 1953*. The New York Times (March 4, 2003).

⁴²² G.E. DUVALL: *Shock wave research: yesterday, today and tomorrow*. In: (Y.M. GUPTA, ed.) *Proc. 4th APS Topical Conference on Shock Waves in Condensed Matter* [Spokane, WA, July 1985]. Plenum, New York (1986), pp. 1-12.

course that predictions of future developments and applications in this field run obvious risks. However, some trends are recognizable. The enormous progress in shock wave and detonation physics achieved within the last 50 years has created a solid foundation of basic knowledge – including shock generation and diagnostic techniques, computational methods of shock analysis, and Hugoniot data on diverse materials and their combinations – which has increasingly also stimulated other disciplines in science and technology. It has created a multitude of interrelations which extend well beyond the historical roots of shock wave physics.⁴²³ Unfortunately, however, this enormous diversity in shockwave-related disciplines has promoted a specialization of knowledge which renders discussions among shock scientists increasingly difficult. For example, gas dynamicists and aeronautical engineers – who are accustomed to working with gases and thinking in terms of mean-free path lengths, viscosity effects, boundary layers, Mach and Reynolds numbers, vortices, *etc.* – can now barely communicate with solid-state shock physicists, who treat shock waves in terms of Hugoniot elastic limits, plastic waves, shear bands, spallation, grain deformation, lattice compression, shock polymorphism, *etc.* Moreover, astrophysicists who studying stellar structures, stellar atmospheres, interstellar material and galaxies in terms of relativity and gravitation, have developed complex mathematical models that describe the physical and nuclear processes in cosmic objects, which are far more complex than the models used in classical gas dynamics and detonation physics.

The ultrarapid nature associated with shock and detonation phenomena have initiated a wide range of new methods for high-speed diagnostics, particularly for high-speed visualization and recording. Obviously, the era of high-speed analog diagnostics is now definitely coming to an end. One of the few exceptions is the pressure gauge technique, which is still

analog. Modern shock physics laboratories use digital, mostly menu-controlled measurement equipment, including not only typical electronic measuring instruments (such as pulsers, delay generators, counters, storage oscilloscopes, pressure-gauge amplifiers, *etc.*), but also digital high-speed cameras. This also implies that photographic film is increasingly being replaced by electronic storage, and that in the near future, high-speed and ultrahigh-speed mechanical cameras – ingenious, optomechanical precision instruments and true servants throughout pioneering decades of shock wave research – will only be seen in technical museums. Surprisingly however, the old-fashioned spark light source – which has been used since August TOEPLER's first shock wave studies in the 1860s and widely modified since then in regard to light intensity, spectral emission, pulse duration and repetition frequency – remains an indispensable and reliable piece of equipment that is applied in many shock tube facilities and indoor ballistic test ranges.

Future trends in shock wave physics are definitely heading towards new frontiers, increasingly encompassing both cosmic and microscopic dimensions. The recently taken “baby” picture of the Universe {⇒ Fig. 4.1–W} confirmed the Big Bang Theory and the previously estimated age of the Universe. Extraterrestrial shock wave diagnostics incorporated in a 720-kg space probe are heading out of the Solar System: as in April 2007, Voyager 1 (launched in September 1977) was over 101 AU (15 billion km) from the Sun, and had thus entered the heliosheath, the so-called “heliospheric termination shock”, also known as the “solar wind termination shock” {Voyager 1 & 2 ⇒ 2003}, where the supersonic plasma of the solar wind begins to slow down as it encounters the interstellar medium. Astrophysicists expect that the termination shock is responsible for the acceleration of interstellar particles which are ionized in the heliosphere and become charged with energies of the order of 20–300 MeV, a fascinating hypothesis known as the “anomalous cosmic-ray component.” At a distance of about 230 AU (34.5 billion km) from the Sun, the Voyager space probes may eventually reach a “bow shock,” caused by the heliosphere itself moving supersonically through the interstellar medium. However, the Voyagers will have exhausted their power supply long before this, by around 2020.⁴²⁴ Indeed, the probing of cosmic shock waves with spacecraft will become a very long-term research program not comparable with any one previously performed in the history of science and – if ever started – it will occupy several generations of astrophysicists.

⁴²³ This suggests the idea of introducing a new term for this interdisciplinary field of research (*e.g.*, *superdynamics*) in order to better differentiate such research from the standard (low- and medium-rate) dynamical methods used in classical mechanical engineering. • In mathematical physics, *superdynamics* denotes a method in which certain terms in the equations of motion are replaced by arbitrary functions [Phys. Rev. Lett. **80**, 972-975 (1998)]. A German and a U.S. company have also adopted this term. When the late Karl VOLLRATH and Gustav THOMER (two German scientists that used to work at ISL) edited in 1967 a compendium of articles reviewing the state of high-speed diagnostics used for the study of shock and detonation phenomena, they chose the book title *Kurzzeitphysik* (“Short Time Physics”) to emphasize the fact that both shock wave and detonation phenomena are high-speed in nature and, therefore, can both be studied using very similar experimental techniques and mathematical methods. The Ernst-Mach-Institut (EMI) in Freiburg, which investigates a wide range of high-rate phenomena, adopted the subtitle *Institut für Kurzzeiddynamik* in 1979.

⁴²⁴ L.A. FISK: *Over the edge?* Nature **426**, 21-22 (2003).

On the other hand, the ultimate goal of materials research is to understand dynamical processes on a microscopic level and to develop mathematical models. More advanced high-speed diagnostics with higher spatial and temporal resolutions may eventually unveil how highly compressed matter with a complex structure (solids and liquids) behaves microscopically directly at and far behind the shock front. Shock compression of solid or porous matter – appropriately called “a physical-chemical-mechanical process” by the Sandia shock physicist Robert GRAHAM⁴²⁵ – is very complex and is not yet fully understood. Over timescales from hundreds of picoseconds to hundreds of nanoseconds, solids are converted to thermodynamic states in which the deformation is fluid-like to a certain approximation. Shock-induced defects at atomic and microstructural levels might lead to local concentrations of mechanical and kinetic energy, resulting in “hot spots.” These defects may play a leading role during the transition from the solid state into fluid-like flow. In addition, changes in chemical composition that occur over ultrashort time durations may introduce substantial complications when analyzing and interpreting the shock-compression process.

In the inanimate realm of simply structured molecules, efforts to understand *high-rate chemical processes* have been pursued for more than a century. Research into shock-induced chemical changes, such as the thermal decomposition of explosive gaseous mixtures, led to the discovery of chain reactions, an important phenomenon in technology, which resulted in the new field of *chemical reaction kinetics*. On the other hand, methods of studying *high-rate physical processes* in the micro world are a challenge to modern dynamic materials diagnostics – such as the fine-structural behavior and rearrangement under the passage of shock waves of crystal lattices, mixtures of fine polycrystalline or even amorphous materials, matrix structures like ceramics, liquids and solids undergoing different types of phase transitions; and porous or multiphase materials. Flash X-ray diffraction experiments have already contributed to a better understanding of the shock loading effects of the unit cell. These exciting studies are presently limited to crystals and microcrystalline substances consisting of elements with low atomic numbers. However, it is quite possible that the “storehouse of creation” (Lord KELVIN) will furnish physicists with more appropriate techniques that will allow this method to be extended to technically relevant high atomic number materials (elements and alloys).

Modern shock wave physics and detonics have also resulted in a broad spectrum of diagnostic methods and instruments for *high-speed visualization* – a rich mine for other branches of science; for example, some of them are now also used in microactuator technology.⁴²⁶ A microactuator is a device a few micrometers to a few centimeters in size which transforms electrical or laser energy into motion. MEMS (Micro-Electro-Mechanical System) technology has been applied in fluid dynamics for active boundary layer control and drag reduction, and has been proposed for use in ballistics for missile and guidance control {LIPELES & BROSCHE ⇒2002}. Microbiology studies that use high-speed visualization to disclose shock-induced rupture effects in laser-irradiated biological microstructures (such as chromosomes) led to the application of this effect as a nano cutting tool (a “nanoscalpel”) in biological cell research {KÖNIG ET AL. ⇒1999}. It is quite possible that in the future similar feedback effects will also result from the combination of *microsystems technology* with *gene technology* and *microbiology*, where shock waves generated as a single pulse or repetitively in a limited space at a well-defined strength would play the role of a *microactuator*. Present ideas for applying shock waves in the bioworld include:

- ▶ the destruction of fatal bacterium and virus strains;
- ▶ the elimination of cancer cells or the prevention of further cancer cell growth;
- ▶ gene manipulation in order to eliminate previously incurable hereditary diseases; and
- ▶ the destruction of white blood cells when treating patients for leukemia, HIV and other diseases, rather than using conventional blood irradiation therapy.

The miniaturization of shock and detonation systems is increasingly discussed in the shock physics community because of numerous promising applications in science, engineering, biology and medical therapy. However, detonation waves as well as shock waves produced by conventional methods in the cm- and m-range cannot directly be scaled down to a microscopic scale, both in regard to their methods of generation and their behavior of propagation and stability. Obviously, the scaling of shock waves {BROUILLETTE ⇒2003} and detonation waves {STEWART ⇒2002} requires new knowledge to be acquired through improved modeling and thoughtful experimentation.

Miniature nanometric shock waves {DLOTT ⇒2000} on a pico-/nanosecond time scale and in a very small shocked volume (a few ng) – so-called “nanoshocks” – can be gener-

⁴²⁵ R.A. GRAHAM: *Shock compression of solids as a physical-chemical-mechanical process*. In: (S.C. SCHMIDT and N.C. HOLMES, eds.) *Shock waves in condensed matter 1987*. North-Holland, Amsterdam etc. (1988), pp. 11-18.

⁴²⁶ P. KREHL, S. ENGEMANN, C. REMBE, and E. HOFER: *High-speed visualization, a powerful diagnostic tool for microactuators – retrospect and prospect*. Microsyst. Technol. 5, 113-132 (1999).

ated in polymeric and polycrystalline solids by irradiation with ultrashort pulses from a Nd:YLF laser. Coherent Raman spectroscopy during nanoshock propagation in a very thin sample can be used to determine the nanoshock wave form which is characterized by the shock front rise and decay times, shock duration, peak pressure, and velocity. The study of microscopic shock effects on a nanosecond time and nanometer size scale, pointing into a new branch of *Nano-Shock Wave Physics*, may be very useful for a number of important applications in macroscopic shock and detonation physics as well as in nano- and microsystems technology. Examples include the understanding of shock-induced (1) chemical reactions; (2) material transformation and mechanical deformation processes; (3) structural compression and relaxation dynamics in organic polymers and biomolecular materials, *e.g.*, proteins; and (4) initiation of detonation in energetic materials, *e.g.*, chemical high explosives. Such experimental studies involve new theoretical model considerations at nanometer size scale.

A much discussed hypothesis on the possible origin of life is how life became organized by spontaneous generation from nonliving matter – a fascinating subject of research which brings together shock physics on a molecular scale (chemical reaction kinetics) with shock physics on a cosmic scale (physical cosmology). The famous Miller-Urey experiment {S.L. MILLER \Rightarrow 1953; \Rightarrow Fig. 4.14–A} gave evidence that amino acids, out of which all life's proteins are made (with few exceptions), can be created by strictly physical-chemical processes, without the help of living organisms. This suggests the idea that on the early Earth the building blocks of life were created from a prebiotic primordial atmosphere under the action of shock and heat. The mix of amino acids found in the well-studied stony Murchison Meteorite { \Rightarrow 1969} was similar to those produced in Miller-Urey-type experiments. It is generally assumed that the

structures of most meteorites were modified on their parent asteroids by a variety of processes including thermal metamorphism and shock metamorphism.

There are still many open questions that laboratory-scale shock wave studies may answer one day. How were these chemical building blocks, essential for life, originally produced? Could shock-induced synthesis have delivered them, for example by meteorite bombardment, in Earth's early history? Future studies in shock wave and impacts physics may play an important role to solve these fundamental questions of biology.

Polycyclic aromatic hydrocarbons (PAHs) are the most complex organic molecules, to that date, found in space {WITT, VIJH & GORDON \Rightarrow 2004}. PAH molecules are thought to be widely present in many interstellar and circumstellar environments in our Galaxy as well as in other galaxies. From the interstellar medium (ISM), a dilute gas and dust that pervades interstellar space, stars are born and when they die stars eject gas and dust back into the ISM. Due to this recycling of material, from stars to the ISM and back into stars, the ISM is enriched with more complex materials and molecules {HOYLE \Rightarrow 1946}; one such group of molecules is the PAHs which is considered of being important for early life.

The discovery of complex organic molecules in space brings the evolution of organic matter into a context with the evolution of stars which, governed by destructive explosion and implosion processes, transmit their “detonation products” via shock waves to remote distances in the galaxy. The concept of modern science that stellar explosions can create complex organic molecules – and possibly proteins, the building blocs of terrestrial life – would confirm in an amazing manner the dualistic principle perceived by some old religions: the opposing ambiguity of creation and destruction; *i.e.*, of life and death.

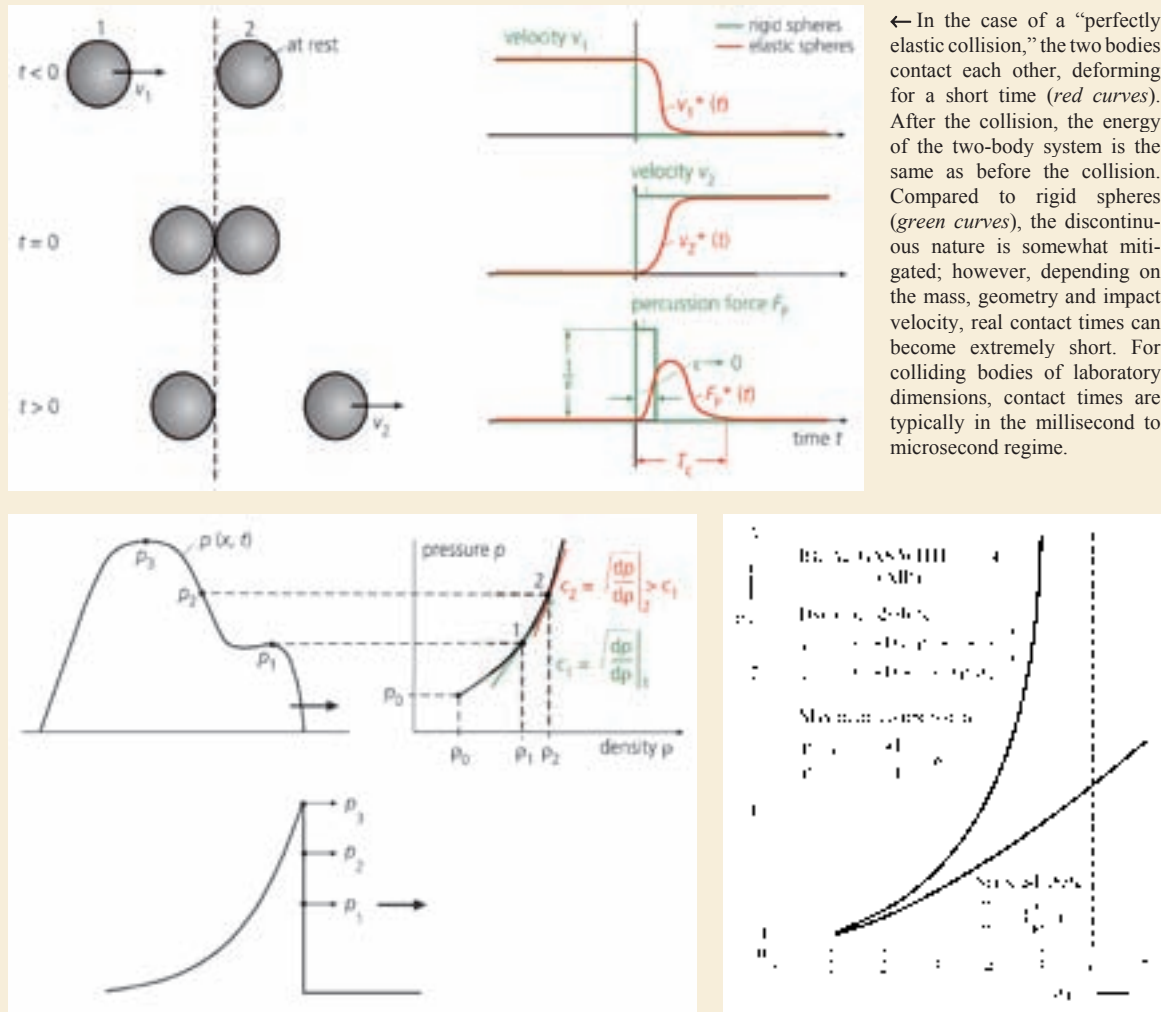


Fig. 2.1 Illustration of the discontinuity problem in classical percussion and shock wave physics. **Top:** When a rigid sphere 1, moving with velocity v_1 along a straight line, strikes a second sphere 2 of the same mass initially at rest head-on, sphere 1 is immediately halted, thereby transferring all of its kinetic energy to sphere 2, which begins to move with velocity $v_2 = v_1$. The velocity-time profiles v_1 and v_2 (green curves) are discontinuous and are, in mathematical terms, called “step functions.” The percussion force F_p becomes extremely large, and acts during only an extremely short time interval – the so-called “contact time” T_c – which can be described by a delta impulse function. [By the author] **Bottom, left:** In shock waves, the discontinuity in most thermodynamic quantities at the shock front is not immediately present, but instead builds up during its propagation and so needs a certain amount of time to develop. For all normal fluids, the plot of adiabatic compression, $p = p(\rho)$, curves upward; i.e., the velocity of any wave disturbance at pressure p and density ρ , measured with respect to coordinates moving with the fluid, is given by $c = (dp/d\rho)^{1/2}$. Therefore regions of higher pressure in the wave-time profile move with a higher velocity, and the ultimate result of this overtaking effect will be to make the front of the shock wave very steep. Typically, pressure rise times at the shock front are very short, on the order of nanoseconds.

[After R.H. COLE: *Underwater explosions*, Dover Publ., New York (1965), p. 24] **Bottom, right:** Schematics of equations of state for an ideal gas with $\gamma = 1.4$ (air). Comparison between the isentrope or “static adiabat” and the “dynamic adiabat” which the French engineer Pierre-Henri HUGONIOT derived in the mid-1880s – the so-called “Hugoniot curve” (or the “Hugoniot” for short). Note that the dynamic adiabat lies above the static adiabat – i.e., it requires a higher pressure to compress a gas to a given density ratio ρ/ρ_0 using a shock wave than in the static case. [By the author]

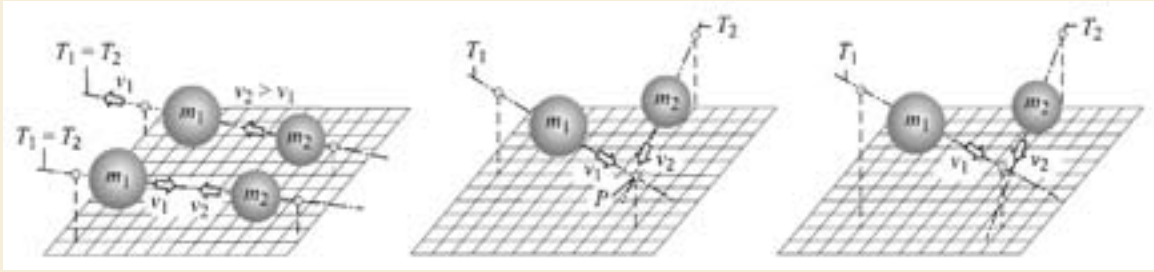


Fig. 2.2 Collisions can take place in one, two and three dimensions. **Left:** Two examples of a *direct central collision* (or *collinear collision*): bodies 1 and 2 move along the same straight line of impact $T_1 = T_2$, the trajectories of the centers of gravity of masses 1 and 2. In this case, they can meet traveling either in opposite directions (a “head-on” collision), or in the same direction with velocity $v_2 > v_1$ (a “front-end” collision). **Center:** *Oblique central collision*: bodies 1 and 2 meet in the same plane, and trajectories T_1 and T_2 intersect at point P . **Right:** *Oblique eccentric collision*: bodies 1 and 2 move along the trajectories T_1 and T_2 , respectively, which don’t intersect. In the special case of the oblique collision of two smooth spheres, there is no tangential force. On the other hand, if friction is present, the translational kinetic energies of the colliding bodies may partly be transformed into rotational kinetic energy and heat, depending on the roughness of the bodies. [By the author]

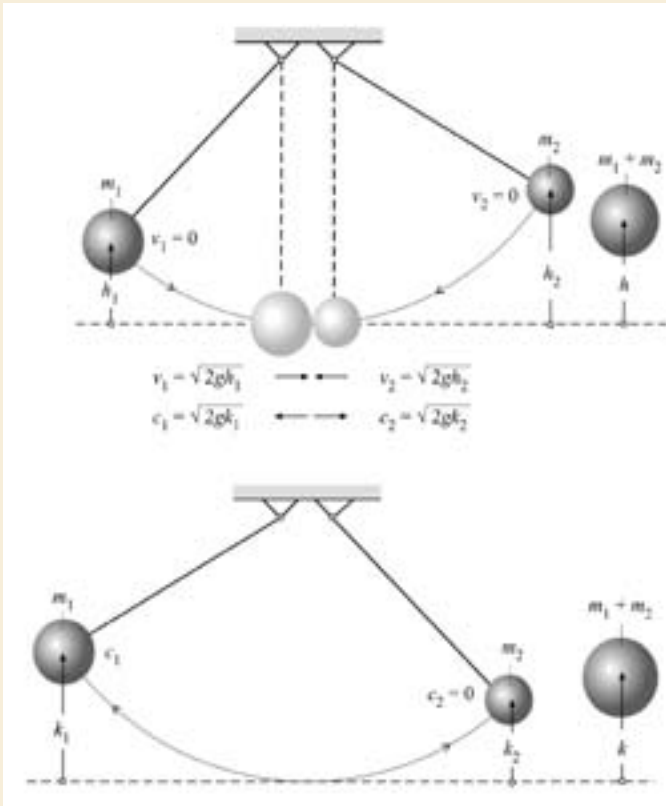


Fig. 2.3 In 1644, the French natural philosopher René DESCARTES defined force F as the product of mass m and velocity v ($F = mv$) which he called the “quantity of motion.” Galileo GALILEI found that a body dropped at height h reaches a velocity $v = (2gh)^{1/2}$. Likewise, a body thrown up vertically with a velocity v reaches a height $h = v^2/2g$. In 1669, the Dutch physicist Christiaan HUYGENS followed GALILEI’s concept and recognized that force can also be defined by its ability to surpass resistance such as gravity, hence $F \propto mh$ or $F \propto mv^2$. He postulated by intuition that “the sum of the products of the magnitudes and the squares of the velocities of the bodies before and after impact are always equal,” thus anticipating the Law of the Conservation of Kinetic Energy.

Top: In the case of a twin pendulum with masses m_1 at h_1 and m_2 at h_2 , the center of mass is given by $h = (m_1h_1 + m_2h_2)/(m_1 + m_2)$. **Bottom:** After releasing the balls simultaneously, they collide with velocities v_1 and v_2 . Rebounding with velocities c_1 and c_2 , they reach the heights k_1 and k_2 , respectively. Then the center of the two masses m_1 and m_2 is given by $k = (m_1k_1 + m_2k_2)/(m_1 + m_2) \leq h$. In the ideal case of perfectly elastic impact and no aerodynamic drag, one has $h = k$, which leads to the Law of the Conservation of *Vis Viva* or “living force”: $m_1v_1^2 + m_2v_2^2 = m_1c_1^2 + m_2c_2^2$. This relation is identical to the Law of the Conservation of Kinetic Energy, given by $\frac{1}{2}m_1v_1^2 + \frac{1}{2}m_2v_2^2 = \frac{1}{2}m_1c_1^2 + \frac{1}{2}m_2c_2^2$. [By the author]

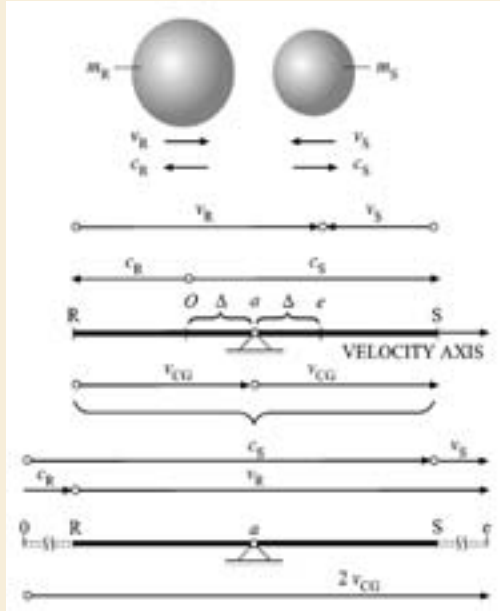


Fig. 2.4 In 1668, the English mathematician and architect Sir Christopher WREN communicated his memoir “Law of Nature in the Collision of Bodies of Motion” to the Royal Society of London. Considering the case of two perfectly elastic bodies R and S meeting each other along a straight line with given velocities v_R and v_S , he proposed an ingenious geometrical solution to find the velocities c_R and c_S after impact. He discovered that “the collision of bodies is equivalent to a balance reciprocating upon two centers equidistant either side of the center of gravity: for the balance may be extended into a yoke when the need arises.” WREN started his geometrical method by plotting the (given) velocity vectors v_R and v_S along the velocity axis. The velocity of the center of gravity of the two masses m_R and m_S is given by $v_{CG} = (m_R v_R + m_S v_S) / (m_R + m_S)$. By applying the known length $\Delta = v_R - v_{CG}$ left from the point “ a ,” the fulcrum of his balance model, he obtains the point “ O .” The velocities after impact, c_R and c_S , are represented by the two distances $O \rightarrow R$ and $O \rightarrow S$ and are given by $c_R = 2v_{CG} - v_R$ and $c_S = 2v_{CG} - v_S$, respectively. Note that since no external forces act upon the system during impact, the velocity of the center of mass is the same before and after impact, hence $v_{CG} = (m_R v_R + m_S v_S) / (m_R + m_S) = (m_R c_R + m_S c_S) / (m_R + m_S)$. This equation leads to the important Law of the Conservation of Momentum: $m_R v_R + m_S v_S = m_R c_R + m_S c_S$. [After Phil Trans. Roy. Soc. Lond. 3, 867 (1669); schematic by the author]

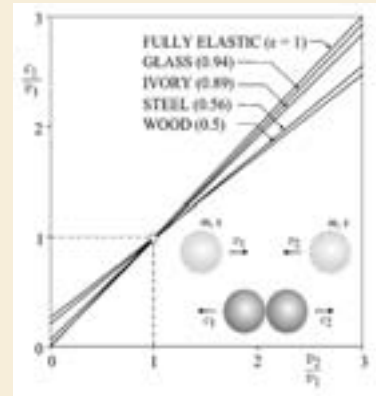
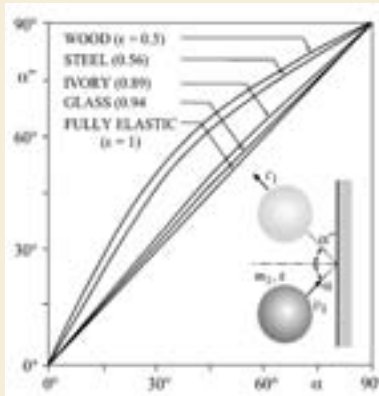
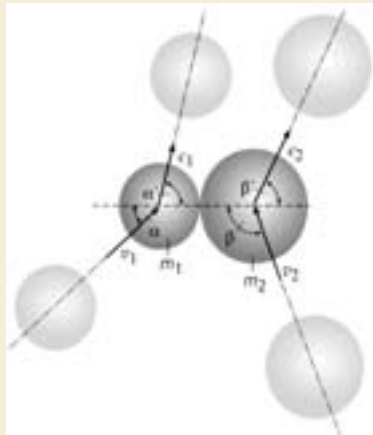


Fig. 2.5 *Left:* The treatment of the *oblique central collision* of two smooth spheres of masses m_1 and m_2 moving in the same plane is one of the fundamentals of percussion theory. Because of no friction, the tangential forces at the point of contact are infinitesimal, and the tangential component of the momentum of each ball is conserved; i.e., $v_1 \sin \alpha = c_1 \sin \alpha'$ and $v_2 \sin \beta = c_2 \sin \beta'$. By applying the Conservation Laws of Momentum and Energy for the normal velocity components, and a given coefficient of restitution ϵ , one obtains $c_1 \cos \alpha' = v_1 \cos \alpha - (v_1 \cos \alpha - v_2 \cos \beta) \times (1 + \epsilon) / (1 + m_1/m_2)$, and $c_2 \cos \beta' = v_2 \cos \beta - (v_2 \cos \beta - v_1 \cos \alpha) \times (1 + \epsilon) / (1 + m_2/m_1)$. [I. SZABÓ: *Einführung in die Technische Mechanik*. Springer, Berlin (1966), p. 372] *Center & right:* There are two special cases of practical interest. For the reflection of a ball of mass m_1 against a solid plane wall (*center*) with $m_2 = \infty$ and $v_2 = c_2 = 0$, one obtains $\alpha' = \arctan(1/\epsilon \tan \alpha)$ and $c_1 = -v_1 \cos \alpha (\epsilon^2 + \tan^2 \alpha)^{1/2}$. Note that in the special case of a perfect elastic percussion ($\epsilon = 1$) the mass is reflected at the angle of incidence ($\alpha = \alpha'$) and $c_1 = -v_1$. For central collision (*right*), one obtains $c_1 = v_1 - (v_1 - v_2) \times (1 + \epsilon) / (1 + m_1/m_2)$ and $c_2 = v_2 - (v_2 - v_1) \times (1 + \epsilon) / (1 + m_2/m_1)$. [By the author]

Fig. 2.6 In 1656, the Dutch natural philosopher Christiaan HUYGENS sent a letter to the French scholar Claude MYLON discussing an interesting three-body percussion problem which has been of enormous importance in practical operations involving hammer/chisel percussion tools since the earliest times. He stated that “a small body striking a larger one, gives it a higher velocity than by direct percussion when a third body of medium size is inserted between both.”

Top: The problem is illustrated in more detail. The small sphere 1 of mass m_1 strikes a large sphere 3 of mass m_3 directly, which results in a velocity c_3 . However, when sphere 1 strikes sphere 3 via an intermediate sphere 2 of medium size and mass $m_2 > m_1$, sphere 3 moves with a velocity $c_3^* > c_3$.

Bottom: As shown in the diagram, the ratio of velocities, $\xi = c_3^*/c_3$, which represents a kind of “gain in percussion,” increases as the ratios m_2/m_1 and m_3/m_2 increase; *i.e.*, the momentum of sphere 3, given by $m_3 c_3^*$, can be increased by incorporating an additional body 2, in a manner analogous to placing a chisel between a hammer and work-piece.

[By the author]

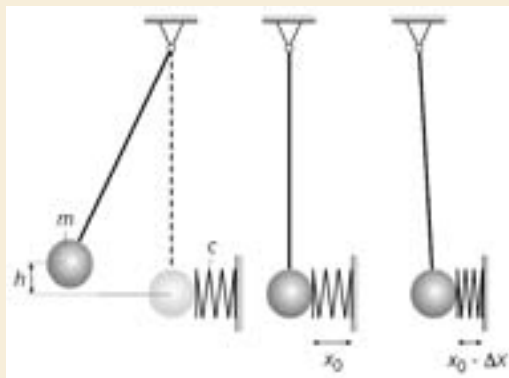
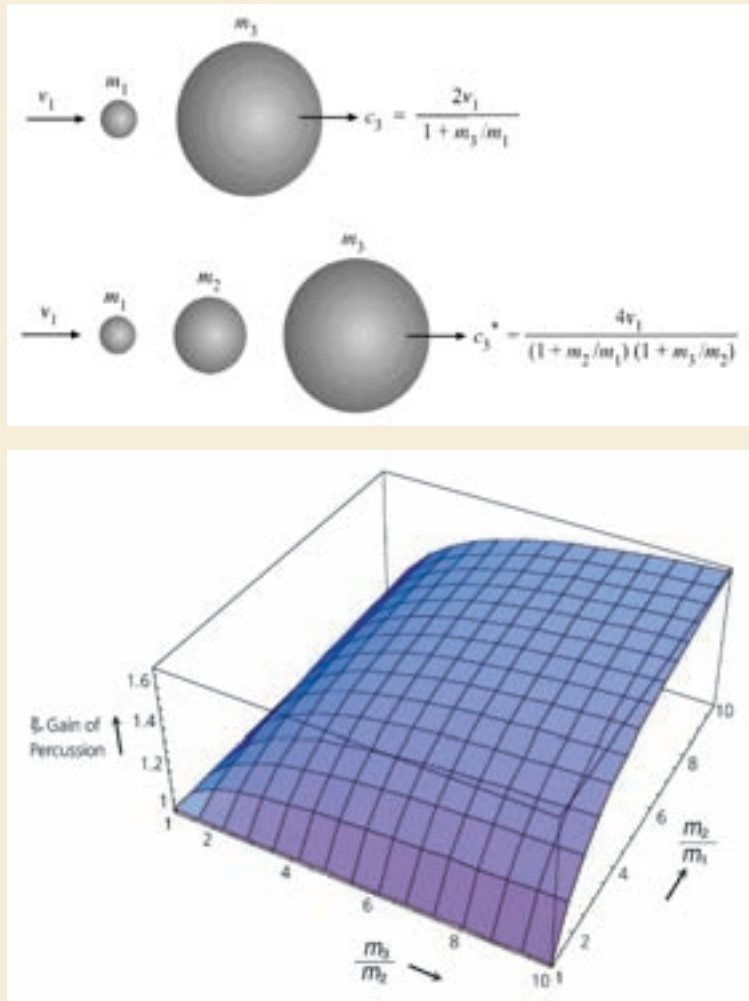


Fig. 2.7 In the pioneering era of percussion research, the *force of percussion* was a rather obscure quantity and was erroneously interpreted by leading naturalists as either the momentum (mv) or the “living force” (mv^2). The maximum force of percussion F_{\max} can be estimated by providing the impacted body with a short spring and recording its maximum deflection Δx during impact. This is demonstrated here for the example of a ball pendulum impacting an ideal short helical spring of stiffness c . **Left:** The mass m , which is initially at rest ($v = 0$), is released at height h . **Center:** At the moment when it touches the spring, the ball has the maximum velocity $v_{\max} = (2gh)^{1/2}$, where g is the gravitational acceleration. **Right:** At the moment of maximum spring deflection, the total kinetic energy of the ball, given by $mgh = \frac{1}{2}mv^2$, is completely transformed into the spring energy $\frac{1}{2}c\Delta x^2$; hence $\Delta x = v(m/c)^{1/2}$ and $F_{\max} = v(mc)^{1/2}$. Note that for a rigid impact ($c \rightarrow \infty$), the maximum force of percussion becomes infinity ($F_{\max} \rightarrow \infty$). [By the author]

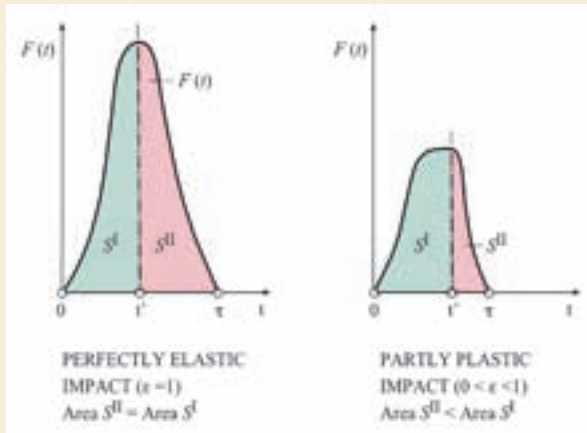
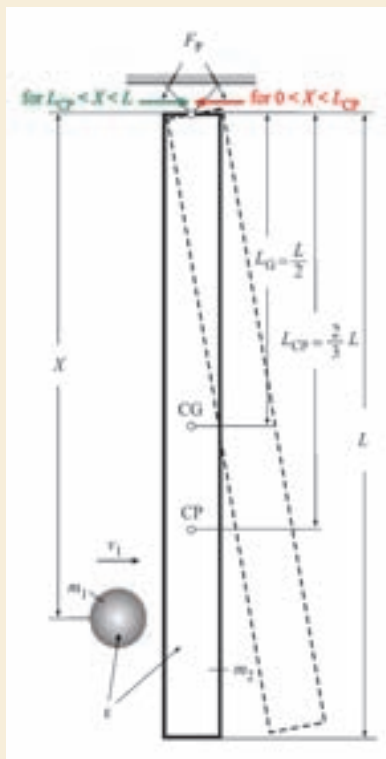


Fig. 2.8 The force of percussion, particularly the way it changes with time $F(t)$, was the source of much speculation among early researchers, because it was not accessible to measurement using the diagnostics available at the time. In his *Traité de mécanique* (Paris 1833), the French mathematician and physicist Siméon-Denis POISSON distinguished for the case of *elastic percussion* (left) between two phases: the first one begins with the contact of the bodies and ends at the highest compression; the second phase begins at that instant and ends when the bodies begin to separate. There is no loss in kinetic energy, and the areas under S^I and S^{II} for both phases, which represent the partial impulses $\int F(t)dt$, are equal. However, in the case of a *plastic impact* (right), the kinetic energy is partly transformed into heat and, therefore, lost in the restitution process; hence $S^{II} < S^I$. [After P. GUMMERT and K.A. RECKLING: *Mechanik*. Vieweg & Sohn, Braunschweig etc. (1986), p. 565]



Left: A vertical compound pendulum consisting of a cylindrical bar of mass m_2 and length L is impacted at distance X from the pivot by a ball of mass m_1 moving at a velocity v_1 . **Right:** Depending on the distance X from the pivot and the coefficient of restitution ϵ , the impact produces either a positive or a negative force F_p in the pivot, which is given by $F_p/F_0 = (1 + \epsilon) \times (\frac{1}{2}X/L - \frac{1}{3}) / [\frac{1}{3} + (m_1/m_2)(X/L)^2]$, where $F_0 = m_1 v_1 / \Delta t$ is the impulsive force. Note that at $X = \frac{2}{3}L$ the force F_p becomes zero; i.e., there is no reaction in the pivot.

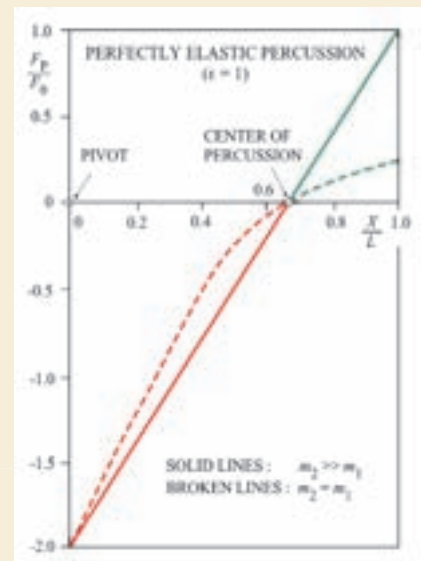


Fig. 2.9 In his treatise *Horologium oscillatorium* (“The Pendulum Clock,” Muguet, Paris 1673), the Dutch physicist Christian HUYGENS described a method that could be used to determine the “center of oscillation” of a compound pendulum – i.e., the point that is vertically below the point of suspension when the pendulum is at rest, at a distance equal to the length of the equivalent simple pendulum. Shortly after, the English mathematician John WALLIS was the first to notice that an impulsive force can be fully transmitted to a freely rotating body when it is struck at its center of oscillation. This will exert no reaction force in the body’s pivot, and so the center of oscillation (CO) is also called the “center of percussion” (CP). Note that the center of gravity (CG) is located above CP. [By the author]

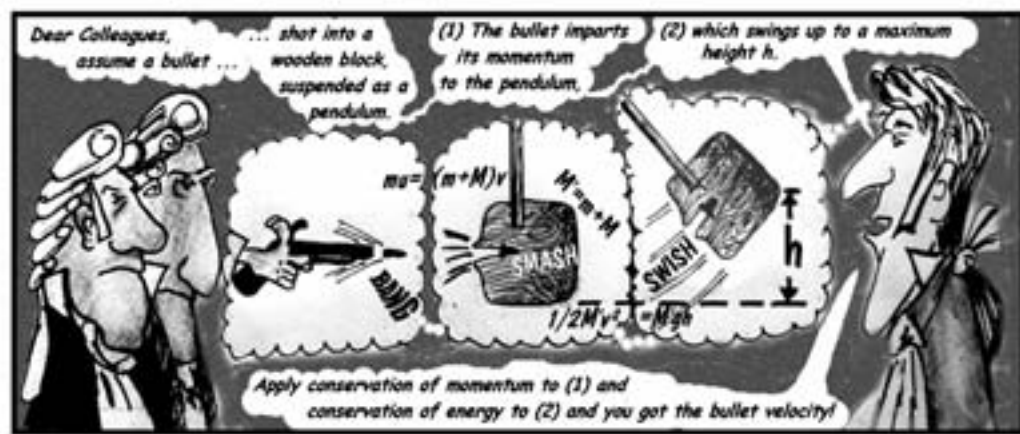


A: In 1636, Marin MERSENNE, a French natural philosopher and priest, determined the velocity of sound in air by firing a cannon and noting the delay between the flash from the muzzle and the arrival of the sound a large distance away – the “flash-to-bang method.” Like Galileo GALILEI in his pendulum experiments, he used his own pulse as a clock. Assuming that one pulse beat takes a second, he obtained a velocity for sound of 450 m/s, which was too large. Today we know that the pulse rate of a healthy person ranges between 60 and 80 beats per minute. In 1737, a French commission was set up to determine the velocity of sound precisely, and they obtained a value of 337 m/s using a chronometer. In his *Principia* (1687), Sir Isaac NEWTON calculated a velocity for sound of only 298 m/s, assuming an isothermal equation of state. The considerable discrepancy between theory and experiment stimulated subsequent generations of natural philosophers, until Pierre-Simon DE LAPLACE (1816) solved this puzzle by showing that sound is an adiabatic process.



B: In 1644, MERSENNE showed that the velocity of a musket ball must be of the same order as the velocity of sound, which he believed to be about 450 m/s (*see above*). He observed that a person positioned near a solid target hears the impact of a musket ball at almost the same instant as the report of the musket. Using this simple method of comparison, he placed the speed of larger missiles at about 180–275 m/s. In order to gauge the possible effect of aerodynamic drag, he also calculated that a musket ball with a velocity of 600 ft/s (209 m/s) must displace 14,400 times its own volume of air during each second of its flight. He concluded that the aerodynamic drag increases with the velocity of the projectile, and inversely with its radius and density, thus explaining the relatively long ranges of large cannon shots [A.R. HALLER: *Ballistics in the seventeenth century*. University Press, Cambridge (1952), p. 107]. Note that in MERSENNE’s era it was not yet technically possible to determine the velocity of a flying projectile. However, his observation that the sound of the impact with the target was heard at almost the same time as the arrival of the muzzle blast was the first indication that the projectile velocity must be on the order of the velocity of sound.

Fig. 2.10 Illustration of six pioneering milestones, A to F, which initiated scientific research into supersonic phenomena. [Cartoons courtesy of Dr. Peter NEUWALD, EMI, Freiburg]



C: In 1707, the Frenchman Jacques CASSINI JR. invented the ballistic pendulum in order to transfer the high velocity of a moving body to a large mass, thus facilitating observation by reducing its velocity. The ballistic pendulum was used in the 1740s in England by the military engineer Benjamin ROBINS, who first measured supersonic velocities (Mach number $M \approx 1.5$) for a musket ball. In the 1780s, his countryman Charles HUTTON, a mathematician and ballistician at Woolwich Royal Military Academy, continued ROBINS' studies. Using a 2-in. (5.08-cm)-caliber cannon and iron balls, he measured supersonic velocities of up to $M \approx 1.87$. It is worth noting that both ballisticians also speculated on aerodynamic drag at high projectile velocities and performed the first quantitative measurements.



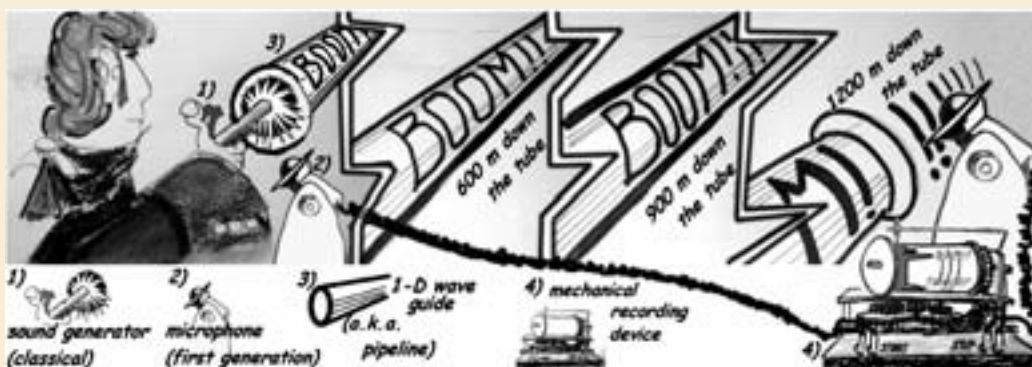
D: During the period 1824–1825, the English polar explorers William E. PARRY, Henry FOSTER and James C. ROSS, whilst searching for the Northwest Passage in Northern Canada, performed sound velocity measurements in dry air at Port Bowen. They used a six-pounder brass gun to produce the sound, and measured the time interval between the muzzle flash and the arrival of the report using a pocket chronometer at a distance of 3.9 km. PARRY, who made the measurement, noticed to his great surprise that the officer's command, "Fire," was distinctly heard to occur about one beat of the chronometer *after* the report of the gun on several occasions. From this observation, he concluded that "the velocity of sound depends in some measure upon its intensity." When Samuel EARNSHAW, an English mathematician and Chaplain of the Queen Mary Foundation in the church and parish of Sheffield, presented the first *Theory of Sound of Finite Amplitude* in 1858 at the meeting of the British Association for the Advancement of Science (BAAS), he (correctly) cited PARRY's observation as experimental proof of his theory that intense sound waves must propagate faster than ordinary sound. However, some contemporary physicists such as the Englishman William GALBRAITH sharply refused this interpretation, arguing that PARRY's observation was influenced by the wind and humidity, neither of which, according to Captain PARRY's journal, were recorded properly.

Fig. 2.10 (cont'd)



E: In 1851, Samuel EARNSHAW, an English clergyman and natural philosopher, observed that “a thunder-storm which lasted about half an hour was terminated by a flash of lightning of great vividness, which was instantly – *i.e.*, without any appreciable interval between – followed by an awful crash, that seemed as if by atmospheric concussion alone it would crush the cottages to ruins. Every one in the village had felt at the moment of the crash that the electric fluid had certainly fallen somewhere in the village ... But, to the surprise of everybody, it turned out that no damage had been done in the village, but that that flash of lightning had killed three sheep, knocked down a cow, and injured the milkmaid at a distance of more than a mile from the village.”

In another case illustrated here, EARNSHAW (erroneously) observed that the thunderclap originating from lightning striking a house 5 km away was heard only two seconds after seeing the lightning. From these curious observations, he concluded that intense sound, such as that emitted from a bolt of lightning, must propagate at an enormous supersonic velocity. A few years later, similar observations were also reported by French natural philosophers. His observations, which he communicated to the British Association for the Advancement of Science, increased his interest in intense acoustic waves, eventually resulting in the first mathematical Theory of Shock Waves (1858).



F: In the mid-1860s, the famous French experimental chemist and physicist Henri V. REGNAULT made careful measurements of the velocity of sound in various gases. He noticed that sound propagating in a tube is less attenuated than sound propagating freely in the atmosphere. In order to obtain precise data on the velocity of sound and to compensate for the limited accuracy of his mechanical chronograph, he used long tubes such as the gas pipeline at Ivry-sur-Seine (a town south of Paris), which was 10.8 cm in diameter and 1,150 m long. By simultaneously triggering his drum chronograph and firing a pistol of one gram of powder at the entrance to the a long pipe, he was able to measure the arrival time of the blast wave at the other end of the tube, using a membrane connected to a mechanical contact as a microphone. This allowed him to determine the average propagation velocity of a blast wave in a tube. In a second experiment, he measured the arrival time of a blast wave propagating freely in air, which quickly loses energy through expansion and turns into an ordinary sound wave. Thus, by simply comparing both of the measured velocities for the propagation of sound, he was able to provide the first quantitative experimental proof that the velocity of sound does indeed depend on its intensity, and that intense sound travels faster than weak sound.

Fig. 2.10 (cont'd)

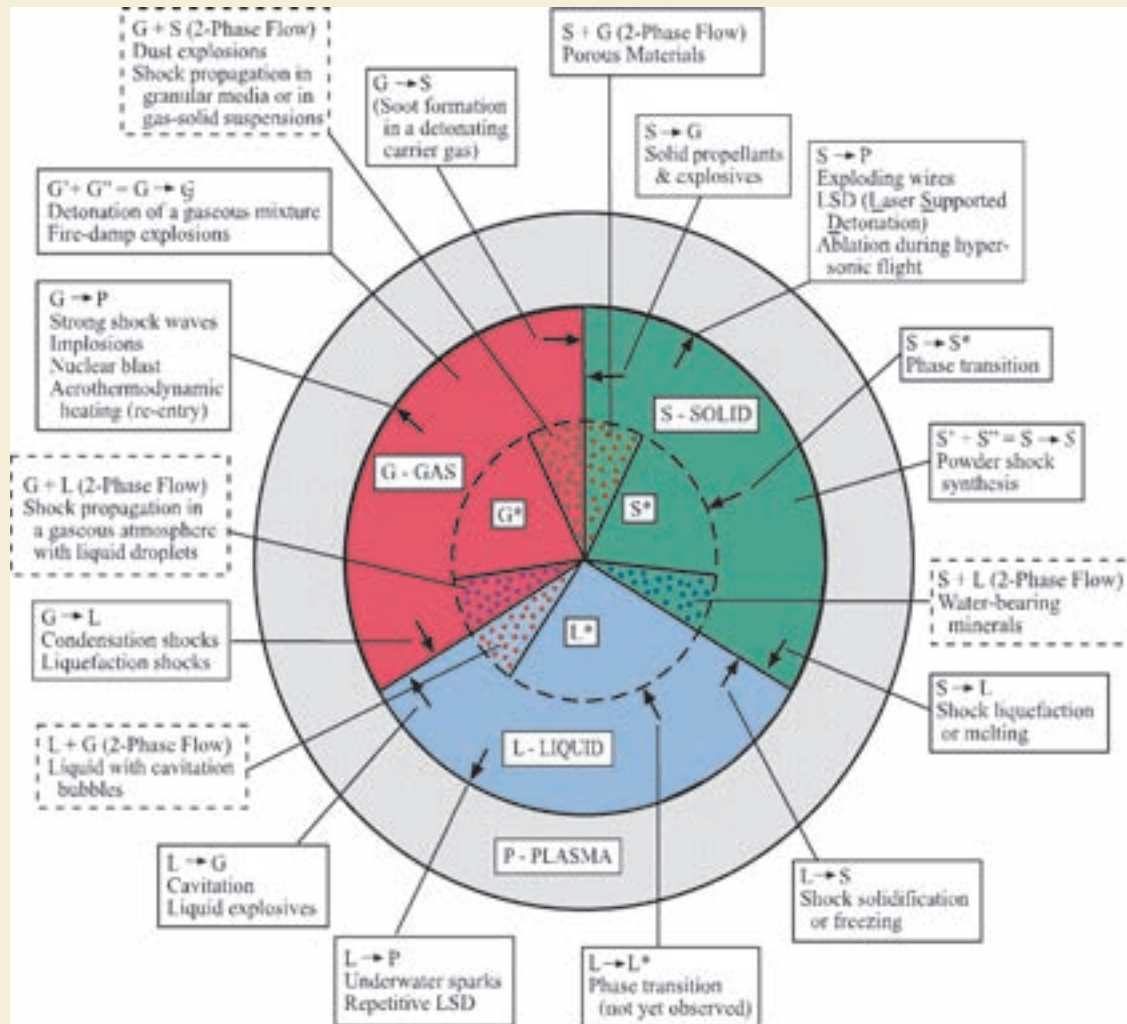


Fig. 2.11 Classification of shock wave physics in terms of phenomena observed in different states of shock-compressed matter (green: S - solid, blue: L - liquid, red: G - gas, gray: P - plasma). Starting from the initial states of matter at rest – G, L and S – shock-induced physical changes are designated by G*, L* and S*, and shock-induced chemical changes by G^* , L^* and S^* . Historically, equation-of-state studies were initially confined to just a single phase, with no chemical or physical changes involved. In many practical cases, however, shock waves propagate in a multiphase medium, which either already exists when the shock is initially generated (e.g., a blast wave propagating in a coal-dust-loaded atmosphere) or is due to the interaction of the shock with the medium itself (e.g., the generation of a cavitation zone by shock reflection at a solid boundary in an underwater explosion). Over the last few decades, shock propagation and interaction phenomena in two-phase or multiphase flows – here indicated by two-color zones: red/blue (gas ↔ liquid), red/green (gas ↔ solid) and green/blue (solid ↔ liquid) – have become of increasing interest to researchers.

[By the author]

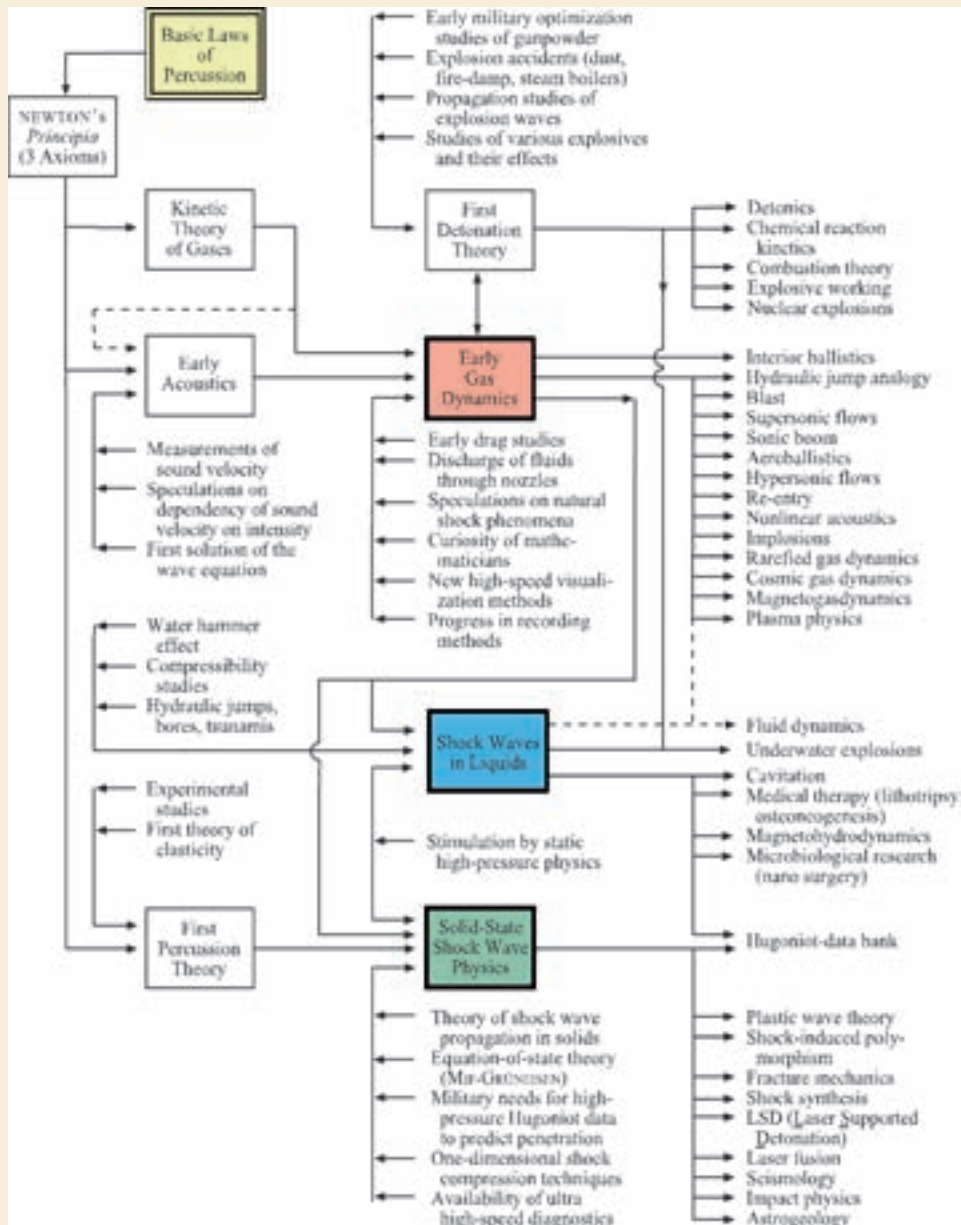


Fig. 2.12 This is an attempt to, through the use of a flow chart, illuminate the complex evolution of the current wealth of shock-wave-related branches of science and technology, which arose through interactions between the various disciplines. This evolution began in the 17th century with studies of classical percussion. *Shock waves* would now appear to be an inadequate term to use to link the many new branches that have evolved over the last 50 years in this field, perhaps a new and more general term would be more appropriate. [By the author]

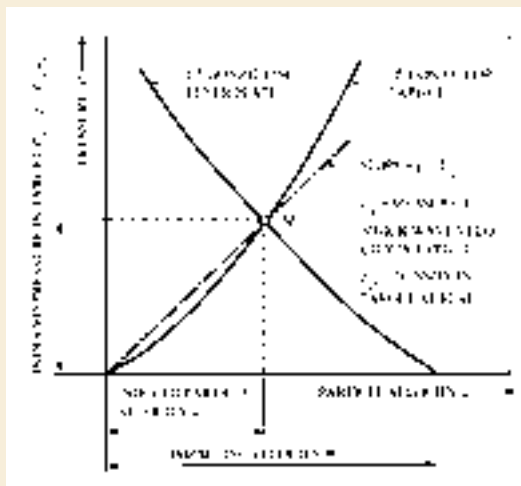
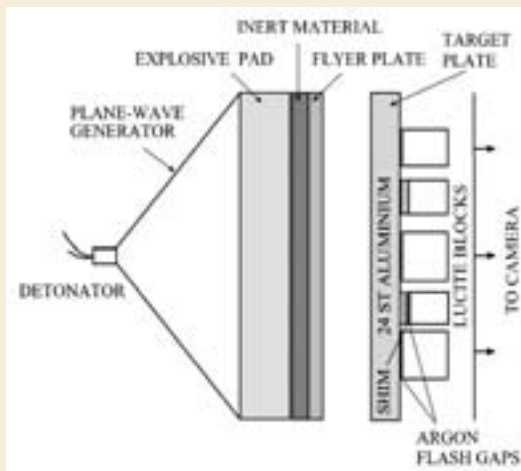
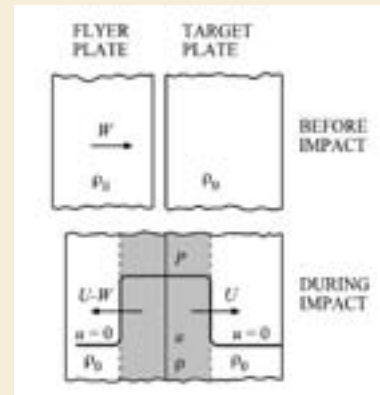
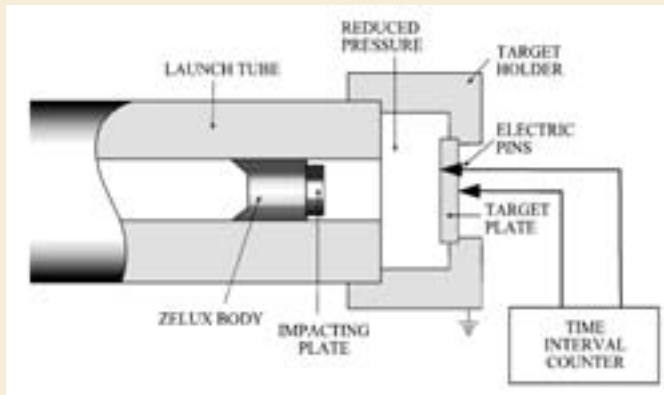


Fig. 2.13 In the laboratory, precisely controlled one-dimensional shock waves are generally produced through the planar impact of a high-density flat plate moving at high velocity into a stationary plate, the so-called “target plate.” **Top, left:** Example of a planar impact using a light-gas gun; here the shock front velocity U in the target plate is measured by electric pins. [After A.H. JONES ET AL.: *J. Appl. Phys.* 37, 3493 (1966)] **Center:** Another example of a controlled planar impact is the “flyer plate” method, which uses an explosively driven plate arrangement; U is measured by the flash-gap technique in this case. The schematic shown here relates to the special case that the target material consists of 24 ST aluminum (94% Al), an alloy that is commonly used as a standard target material for determining Hugoniot curves of other solid materials. [After G.E. DUVAL and G.R. FOWLES: *Shock waves*, In: *High Pressure Physics and Chemistry*, Academic Press, New York (1963), vol. 2, p. 209] **Top, right:** Schematic of shock propagation in target and flyer plate shortly after impact, illustrated here for the special case where the flyer and target are made of the same material. Before impact (*top*) the flyer is traveling at a velocity W , and the target is at rest. Just after impact (*bottom*), the material on either side of the impact interface has been compressed to a density ρ , raised to a pressure P , and accelerated to a particle velocity u . The pressure as a function of the distance is also shown, superimposed on the schematic. The material at the contact surface is shown propagating into the flyer and the specimen at a velocity U relative to the material, the “shock front velocity.” The motion of the contact surface, which creates shock waves in both the flyer plate and the target plate, can be compared to the piston surface of the piston model used in gas dynamics {⇒ Fig. 4.4–D}. The standard material most widely used for the flyer plate is the alloy 24 ST aluminum; its Hugoniot has been determined very precisely. [After W.J. MURRI and D.R. CURRAN, Tech. Rept. 001-71, Poulter Lab., SRI, Menlo Park, CA (1971)] **Bottom, left:** Schematic of plane shock waves induced by planar impact. For a “symmetric” impact (*i.e.*, when the flyer and the target are made of the same material) the particle velocity u imparted to the target is exactly one-half of the projectile velocity W . The impact produces a wave (traveling to the right) in the target, which is initially in the state $P = 0$, $u = 0$. The stopping shock produced in the flyer plate lies on the reflected Hugoniot through $u = W$, and the direct shock induced in the target lies on the direct Hugoniot curve of the target. The common state produced by impact lies at the intersection M of the two curves. [By the author]

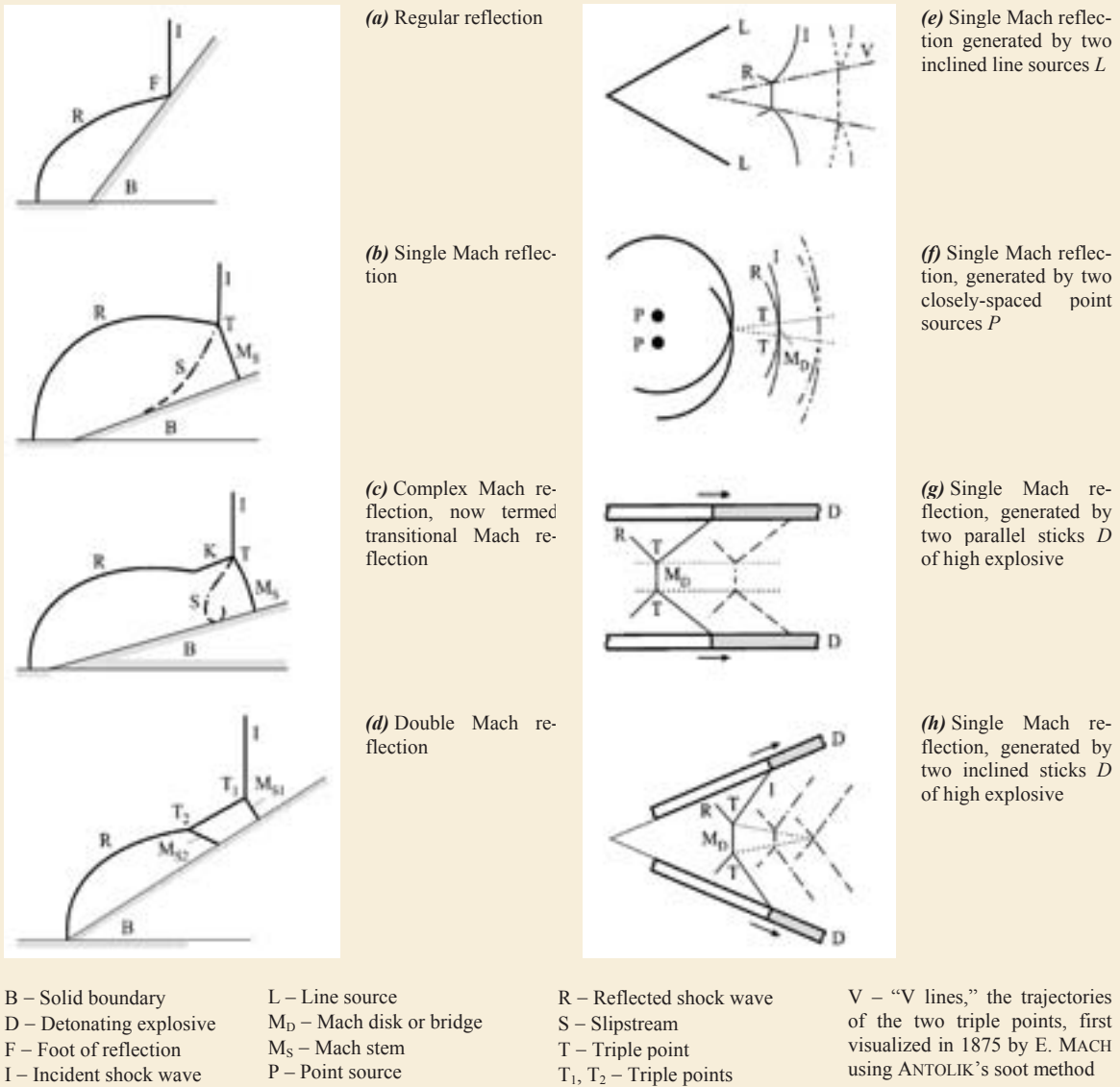


Fig. 2.14 There exist four basic types of nonstationary oblique shock-wave reflection: **(a) regular reflection** and **(b) single Mach reflection** {E. MACH & WOSYKA \Rightarrow 1875}; **(c) complex Mach reflection** or **transitional Mach reflection** {SMITH \Rightarrow 1945}, and **(d) double Mach reflection** {WHITE \Rightarrow 1951} – the last three types being termed *irregular reflection*. Mach reflection, an important area of shock wave research, has been studied in great detail since the 1940s using either a plane shock wave generated in a shock tube and impinging on a plane wedge, or by the interaction of spherical or cylindrical shock waves emerging from electric sparks, exploding wires, or by the detonation of high explosives. Depending on the selected geometry, one can differentiate between asymmetric Mach reflection phenomena **(a–d)** and symmetric Mach reflection phenomena **(e–h)**. Advantageously, symmetric arrangements don’t require a solid boundary and are particularly useful for producing extremely high dynamic pressures. In the cases **(b–d)** and **(e–f)**, the Mach stems and Mach disks, respectively, increase with time (“progressive Mach reflection”). In case **(g)**, the size of the Mach disk remains the same over time (“steady Mach reflection”). Case **(h)**, which depicts a configuration in which the Mach disk decreases in time, is called “inverse Mach reflection” (or “regressive Mach reflection”). [By the author]

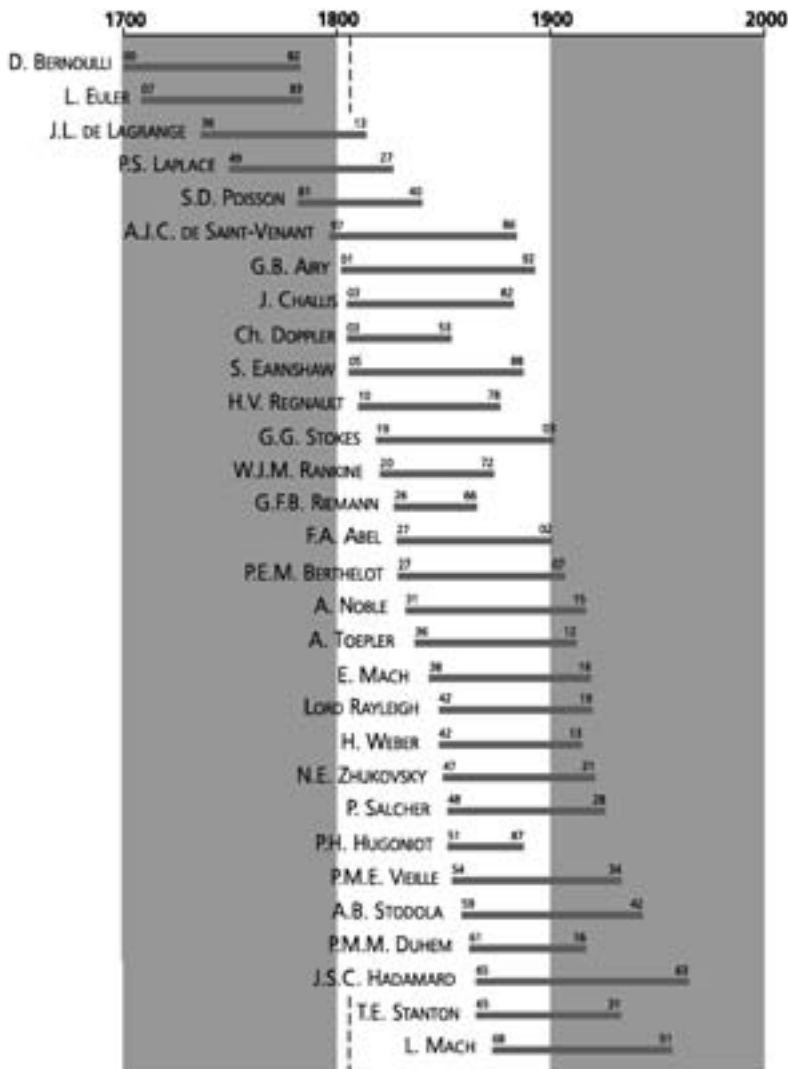


Fig. 2.15 Life spans of some renowned percussion, explosion and shock wave researchers. The beginning of the *Shock Wave Era*, marked by the vertical broken line, can be attributed to the French mathematician and physicist Siméon-Denis POISSON, who in 1808 was the first to analytically treat “waves in which the velocities of the molecules are not supposed to be very small” {⇒ Fig. 2.17}. [By the author]

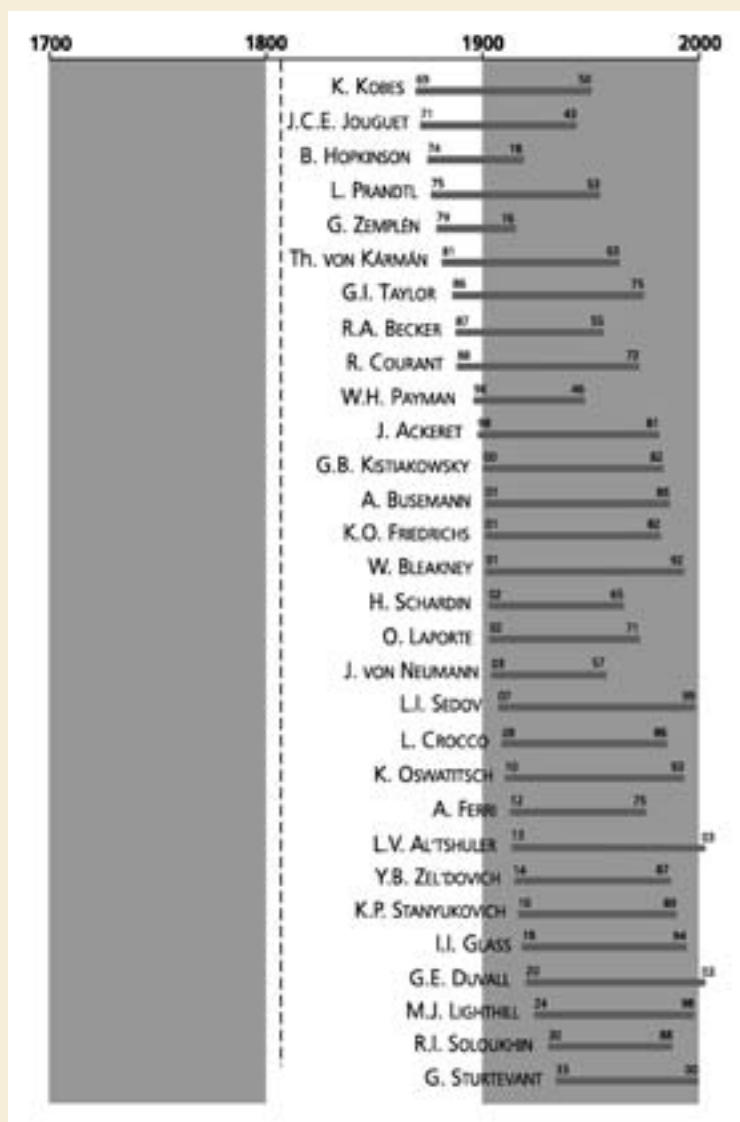


Fig. 2.15 (cont'd)

16 **LE JOURNAL**
EXTRAIT D'UNE LETTRE DE M. HUYGENS
à l'usage du Journal.

Il faut considérer, comme l'on peut, les propriétés touchant le mouvement de percussion, c'est à dire le mouvement qui se produit par la rencontre des corps. Cette matière a déjà été traitée par plusieurs auteurs, mais de se fier, avec une fidélité, à l'un d'eux, le P. Fabri, & depuis peu par M. Borelli, de laquelle le second a été maintenant le plus sûr. Mais si tout cela, les écrivains que ma Théorie s'accorde parfaitement avec l'expérience, & que se la être fondée en bonne démonstration, comme s'il ne s'agit d'une loi bien établie en la Science du public.

Règles de mouvement dans la rencontre des Corps.

1. Quand deux corps se rencontrent directement en une ligne droite, qu'ils étoient l'un en repos, l'autre en mouvement, & demeurent immobiles après la rencontre.

2. Mais si ces deux corps se rencontrent, & qu'ils soient en une même ligne droite, ils sont en échange réciproque de leur mouvement.

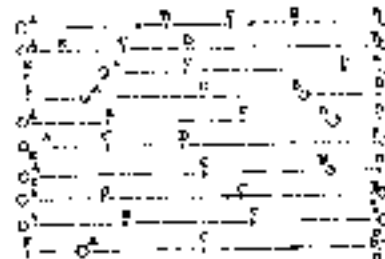
3. Un corps quelconque peut qu'il soit, & quelque grand qu'il soit, en repos, en rencontre un autre plus grand qu'il soit en repos, lui donnera quelque mouvement.

4. La règle générale pour la rencontre de mouvement qu'ils acquièrent les corps dits par leur rencontre directe, est celle.

Solent les corps A & B, de laquelle A soit une avec la vitesse AD, & que B soit la rencontre ou bien soit le mouvement avec la vitesse BQ, ou que même il soit en repos, le point D en ce cas sera le même que B. Avant la rencontre dans la ligne AB le point C est le centre de gravité des corps A & B. On prendra C, E égal à CD, & l'on aura EA pour la vitesse du corps A après la rencontre, & EB pour celle du corps B, & l'on se l'ou-

DES SÇAVANS.

se voit le côté des lettres l'ordre des points A, E, B, & l'ordre des lettres que le point C tombe en A ou en B, les corps A ou B soient redoublés selon.



5. L'égalité du mouvement qu'une deux corps, se peut augmenter ou diminuer par leur rencontre; mais il y a celle qu'on jette la même quantité transmise ou réfléchi, & l'autre la quantité du mouvement contraire.

6. La somme des produits faits de la grandeur de l'un quel corps par sa vitesse, & du carré de sa vitesse, est toujours la même avant & après leur rencontre.

7. Un corps dur qui est en repos, & rencontre un plus grand mouvement d'un autre corps plus grand ou moindre que lui, par l'interposition d'un tiers de grandeur moyenne, que si l'on étoit frappé immédiatement; Et si ce corps interposé est moyen proportionnel entre les deux autres, il sera le plus d'impression sur celui qui est en repos.

Et considérez en ces cas ces deux corps d'une même nature, ou bien entendez que leur grandeur soit estimée par le poids.

Aussi se l'ay remarqué une loi admirable de la Nature, laquelle puis démontrer en ce qui est des corps sphériques, & qui semble être générale en tous les autres.

Fig. 2.16 In 1669, the Dutch physicist Christiaan HUYGENS published his *Règles du mouvement dans la rencontre des corps* (“Laws of Motion on the Impact of Bodies”) for the first time in the French *Journal des Sçavans*. An English translation of his rules can be found in the CHRONOLOGY {HUYGENS ⇨ 1669}. His most important result is rule 6 (right), which says that “the sum of the products of the magnitudes and the squares of the velocities of the bodies before and after impact are always equal” – this represents the birth of the Law of the Conservation of Kinetic Energy. In the same year, HUYGENS also published the same article in Latin (which was the international language among scholars at that time) in the English journal *Philosophical Transactions*. His important contributions to the laws governing impact made his work a cornerstone of classical mechanics. [Journal des Sçavans (Paris) 5, 22-24 (March 18, 1669)]

• The *Journal des Sçavans*, the earliest scientific journal, was established in January 1665 in Paris. The figure shows facsimiles of the first two pages of HUYGENS’ paper at a somewhat reduced scale. Note the small format of this journal. The first issues of this journal were reprinted in 1679 in Amsterdam at an even smaller scale: they had a page size of only 13 × 7 cm².

§64

ANALYSE.

que *N* a été déterminée, le premier, entre la vitesse du son donnée par le calcul, et celle qui résulte de l'observation.

Mouvement d'une ligne d'air dans le cas où les Vitesse des molécules ne sont pas supposées très petites.

[25] En supposant que la masse d'air se réduise à une simple ligne, et en prenant cette ligne pour l'axe des abscisses, les quantités ρ et ϕ ne seront plus des fonctions que de x et t , et si l'on fait abstraction de la pesanteur, les équations (a) et (b) du n° 1 deviendront

$$\int \left(\frac{\partial \rho}{\partial t} + \frac{\partial \phi}{\partial x} + \frac{1}{2} \left(\frac{\partial \phi}{\partial x} \right)^2 \right) dx = 0,$$

$$\frac{\partial \rho}{\partial t} + \rho \left(\frac{\partial \phi}{\partial x} \right)^2 + \frac{1}{2} \left(\frac{\partial \phi}{\partial x} \right)^2 = 0.$$

Si l'on suppose de plus la température constante dans toute la ligne d'air, la pression p sera proportionnelle à la densité ρ , et l'on aura $p = c^2 \rho$, c étant un coefficient constant qui représente la racine carrée du rapport de l'élasticité de l'air à la densité, avant que le mouvement ait commencé. La première de ces équations deviendra donc

$$c^2 \rho \left(\log \frac{\partial \rho}{\partial t} + \frac{\partial \phi}{\partial x} + \frac{1}{2} \left(\frac{\partial \phi}{\partial x} \right)^2 \right) = 0. \quad (1)$$

En ôtant le densité de l'air avant le mouvement, éliminant ρ entre celle-ci et l'équation précédente, on trouve

$$\frac{\partial \phi}{\partial t} + c^2 \left(\frac{\partial \phi}{\partial x} \right)^2 + \frac{1}{2} \left(\frac{\partial \phi}{\partial x} \right)^2 = c^2 \frac{\partial \phi}{\partial x}. \quad (2)$$

L'intégrale complète de cette équation est impossible sous forme finie. Il est facile de s'en assurer, en lui appliquant la méthode que M. Laplace a donnée pour intégrer les équations aux différences partielles du second ordre, après l'avoir ramené à la forme linéaire, que cette méthode suppose, au moyen d'une transformation, connue que l'on doit à M. Legendre. Cette transformation linéaire est comprise parmi les équations que M. Laplace a intégrées, par le moyen d'une intégrale

Fig. 2.17 Facsimile of the page of Siméon-Denis POISSON's *Mémoire sur la théorie du son* ("Memoir on the Theory of Sound") in which he first addresses the special case that "the velocities of the molecules are *not* very small." His result – essentially a simple wave solution of the differential equation of flow in an isothermal gas – stimulated subsequent researchers to work in this area. The first was James CHALLIS (≈ 1848), who observed that POISSON's solution cannot always be solved uniquely for a given velocity, followed by Sir George G. STOKES (≈ 1848), who was the first to apply both the Law of Conservation of Mass and the Law of Conservation of Momentum to the problem, thus deducing two discontinuity conditions for an isothermal gas. [J. Ecole Polytech. 7, 319 (1808)]

qui ne sont autres que celles des paragraphes précédents, où l'on a changé le signe de $\frac{dx}{dt}$.

La deuxième de ces relations montre que $v = v_1$ et $z_1 = z$ sont finies en même temps. Ainsi toute variation brusque de vitesse entraîne pour la tranche une variation brusque de dilatation.

On déduit d'ailleurs de ces relations

$$p_1 = p \frac{2(1+z) - (m-1)(z_1-z)}{2(1+z) + (m-1)(z_1-z)},$$

formule d'une haute importance qui permet de calculer la pression finale au moyen des données initiales et de la variation survenue dans la dilatation.

La formule peut être mise encore sous une autre forme. Soient $\bar{\rho}$ et $\bar{\rho}_1$ les densités correspondant aux dilatations z et z_1 ; il est visible que

$$p_1 = p \frac{(m+1)\bar{\rho}_1 - (m-1)\bar{\rho}}{(m+1)\bar{\rho}_1 + (m-1)\bar{\rho}},$$

ou

$$p_1 = p \frac{(m+1) \frac{\bar{z}_1}{\bar{\rho}} - (m-1)}{(m+1) - (m-1) \frac{\bar{z}_1}{\bar{\rho}}}.$$

Le rapport des pressions est ainsi une fonction rationnelle du rapport des densités.

La pression p_1 est essentiellement positive, ce qui fixe des limites que ne peut dépasser le rapport $\frac{\bar{z}_1}{\bar{\rho}}$.

Supposant d'abord ce rapport supérieur à 1, ce qui arrive quand la variation brusque a pour effet de comprimer la tranche, le numérateur est toujours positif; il faut qu'il en soit de même du dénominateur.

Donc

$$\frac{\bar{z}_1}{\bar{\rho}} < \frac{m+1}{m-1}.$$

Si, au contraire, la variation brusque a pour effet de dilater la tranche,

Fig. 2.18 (*cont'd*) Facsimile of page 88 from HUGONOT's second part of his great memoir in which he derived his famous "dynamic adiabat" $p = p(\rho_1/\rho)$ for an ideal gas – today known as the "Hugoniot" (short for "Hugoniot curve"), which is given by the highlighted equation. He used the letter m (instead of γ) for the ratio of specific heats, c_p/c_v . Note that in the (p, ρ) -plane the dynamic adiabat is steeper than the static adiabat, as illustrated in Fig. 2.1. [J. Ecole Polytech. 58, 88 (1889)]

History of Shock Waves, Explosions and Impact

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Krehl, P.O.K.

2009, XLIV, 1288 p. In 2 volumes, not available
separately., Hardcover

ISBN: 978-3-540-20678-1