

Chapter 2

Preliminary Aspects of Classical Physics

2.1 Newton and His Laws of Motion

Before we get to Einstein's Relativity, we should start with Isaac Newton, who was another genius and also, in his own way, a relativist. Many, including ourselves, feel that Newton and Einstein were the greatest physics geniuses of all time. We constantly contemplate with awe what these two giants of insight and imagination have achieved, how dominant have been their respective contributions to the evolution of physics. Our focus will be on Einstein but it was Newton who most significantly set the stage for what was to come. No physics treatise can logically skip over him. Besides developing, in parallel with Leibniz, the indispensable mathematical discipline of calculus, Newton formulated three important Laws of Motion and actually, he had his own Principle of Relativity. These motion laws are very simple:

1. A body at rest remains at rest and a body in motion, continues in motion in a straight line with constant speed unless it is subjected to an unbalanced force.

In other words, left undisturbed, bodies keep moving uniformly in the way they have been moving. In fact, they will do so even if there are forces (pushes and pulls) on them as long as any given force is compensated for by an equal and opposite force, restoring the balance. But if there is a force on the body that does not have a balancing partner, Law 2 comes into play:

2. If an unbalanced force acts upon a body, it is accelerated, i.e. it changes its speed and/or its direction of motion. The extent of the acceleration is proportional to the strength of the unbalanced force and the direction of the acceleration is in the direction of the unbalanced force.

In other words, if forces on a body do not balance out, the body will *not* continue to move as it had been moving prior to being subjected to the unbalanced force. Rather, it will be accelerated, i.e. it will speed up or slow down and/or change its direction of motion, depending on which way it had been moving beforehand and which way the unbalanced force was directed. Physics students remember this law in equation form,

$$F = ma \quad (2.1)$$

with F the unbalanced force, a the acceleration and the proportionality factor m is the mass of the body. Notice that for a given F , the bigger the m , the smaller the a . This is right in line with our everyday experience: the more massive a body, the less it will get going for a given push.

You might get confused about these two laws if you do not realize that friction is another force and it's hard to get rid of friction. But imagine a hockey puck sliding on a sheet of very smooth ice, approximating the elimination of friction. The puck just keeps going at a (nearly) steady speed in the same direction; the smoother the ice sheet, the further it goes. However, if you were to give the puck a solid smack with the hockey stick, it would speed up dramatically, and the harder the smack, the more it would speed up. Of course it does so in the direction at which it had been smacked. These laws are part of our everyday experience and make excellent sense. The Third Law is a bit more subtle:

3. *For every action, there is an equal and opposite reaction.*

If you push against the wall, the wall pushes directly back against you: action, the push, reaction, the push back. It might sound strange to think that a wall can push you but it must. The friction force on your shoes is pushing you toward the wall because you are pushing backwards on the floor (again a case of action and reaction) and since you are not moving at all, the wall must be pushing you in the opposite direction to keep the forces balanced (Law 1). So it all makes sense.

These laws plus Newton's law of "universal gravitation", that every body in the universe attracts every other body with a force F that is proportional to the product of their masses m and M and inversely proportional to the square of the distance r between them, in equation form

$$F = GmM/r^2 \quad (2.2)$$

(G is the constant of universal gravitation) are the bases of the important part of physics called "classical mechanics". It governs much of our everyday physical life-experience.

2.2 Frames of Reference

Of course the application of Newton's laws requires measurements. The measurements to which Newton's laws apply occur within frames of reference called "inertial". A frame of reference is a grid to which we can ascribe the positions of bodies at any given times.¹ In other words, it is Newton's laws that pick out inertial reference frames. A reference frame is not inertial if it is accelerated, for example a frame of

¹ Imagine a set of three mutually perpendicular sticks with markings at one centimeter intervals. This constitutes a reference frame. A particle's position is specified by its three-number set of position coordinates relative to this frame.

reference that is anchored to a rocket-ship while its rockets are propelling it to higher and higher speeds. Newton's laws do not hold in such a reference frame. After all, if you were to gently release a coin in such a frame, it would not stay put but rather it would move with accelerated motion in the direction of the rockets. Since there would not be any force acting on this released coin, its accelerated motion relative to the rocket-ship frame of reference would be in violation of Newton's First Law.

Newton's Principle of Relativity states that the dynamical laws of physics are the same relative to all inertial reference frames. The word "all" leads us to ask how we can generate more inertial reference frames, once we have determined a single inertial reference frame. This is easy: from one, we can create as many as we wish by simply moving with respect to the first with a constant velocity² (motion at a constant speed in a straight line of specified direction). The laws hold relative to these frames as well because bodies that are not subjected to unbalanced forces will still continue to move at constant velocities relative to these frames; all that happens is that each original constant velocity will just change to a new constant velocity as a result of the transformation.

In addition to the grid, we have to bring into the discussion a set of clocks to be able to determine where any given body is located as well as when it is there. For example, from a given starting point (let us say your position), the body could be 3 m to the west along the east–west line, 5 m to the north along the north–south line and 14 m up along the vertical line. Suppose it is there at a time 10, the time you set your clock to start. Those four numbers really pin it down. We would write the body's coordinates in time (the first number) and space (the second, third and fourth numbers) as a bracketed unit (10, 3, 5, 14). Physicists call this set of four numbers describing the body's position in space and time an "event" even though, as events go, this one is not really all that dramatic. It is an event in the combination of space and time we refer to as "spacetime". In our experience, it is *four-dimensional spacetime*, three dimensions of space and one dimension of time; we do not perceive any dimensions beyond these.³ It is worth pondering for a moment why this is the case. Why do we not live in a universe with one spatial dimension? With two spatial dimensions? With four, five, six, etc. spatial dimensions? Some have even considered the notion of more than one time dimension.

If the body just stayed there relative to our grid, the first number 10 would change (ignoring smaller uncrements) to 11, 12, 13, etc. as the clock ticks away while the other numbers would remain the same. However, if the body were to be in motion relative to the grid, all of the numbers could be changing continuously as we trace out the body's history in spacetime. This grid, populated by clocks, constitutes an inertial frame of reference if Newton's laws of motion hold true relative to this frame.

² In physics, the word "velocity" takes on a very specific meaning; it has two aspects, speed that only tells you how fast the object is moving and second, direction, which way it is headed at that instant. It is indicated in physics diagrams by an arrow pointing in the motion direction with length of arrow indicating the degree of speed.

³ Some researchers have dealt with higher-dimensional spacetimes but primarily with having the extra dimensions curled up into such an incredibly small size that they are beyond our ability to detect them.

It is worth repeating: it would not be inertial if the grid were attached to a rocket ship while the engines are blasting away. As well, it would not be inertial if it were rotating. Such frames are accelerated. Accelerated reference frames are called “non-inertial” and Newton’s laws do not hold true relative to such frames. Also, it is worth repeating the example for emphasis: relative to the rocket ship frame, if you were to release a coin from rest inside the rocket ship, it would not stay put as Newton’s First Law would have it but rather, it would move with acceleration in the direction to which the gases are being propelled away from the ship, just as if it had been dropped from rest as you stand on earth.⁴

2.3 Let There Be Light

We now have some of the basics that we need. The next step is to bring into the discussion the very mysterious and wondrous thing we call “light”. Wondrous indeed! Imagine a universe without light. How fortunate we are to have eyes that permit us to partake of all the beauty that surrounds us and how fortunate we are for the protection that light provides for us from the many potential hazards that we face. It is even more spectacular when we probe into its essential nature. Newton had regarded light as a stream of “corpuscles”, much like a hail of miniscule pellets, while Huygens claimed that light was really a wave. Curiously, in modern physics, we regard *both* Newton and Huygens as being right! Light has a dual nature, a particle aspect and a wave aspect. In modern parlance, Newton’s corpuscles are called “photons”. The wave aspect of light is most apparent in the many experiments that have been performed to probe its character.⁵ But what do we know of waves? There are sound waves, waves that propagate in air and through water, generated by chains of molecules set into vibration. There are water waves in the seas and the oceans, there are waves traveling on a vibrating string. Common to all the familiar waves is the presence of a medium, some form of matter to “wave” the propagating disturbance. Physicists had reasoned that since we see the light reaching us from the distant stars and since the atmosphere above the earth trails off rapidly in the near emptiness of interstellar space, there must be some very rarified residual medium present to support the “waving” of light. This supporting medium must be so rarified that we cannot detect its presence in the obvious ways that we detect the media for the common waves that we mentioned. This medium was given a name: The “ether”, and much of the then world of science was just as confident of its existence as it was of the existence of the traditional media, molecules, bulk water and string material respectively in the previous discussion. It is well to remember the ether when we convince ourselves that some form of matter must exist to satisfy some cherished

⁴ In fact this phenomenon will serve as part of our lead-in to an understanding of General Relativity.

⁵ Other experiments bring out the dual particle character of light. See the photo-electric effect discussed later.

theory. The theory, however seemingly inevitable, necessary and wonderful, might nevertheless be wrong. It is nature that decides.

In this regard, we must remind ourselves constantly that an essential element of any science is experimental verification. Michelson and Morley set out to detect this ether in an ingenious experiment. They reasoned that as the earth moves through the ether, an ether wind, however subtle, must be created. With the earth moving at speed v through the ether, light would have a retarded upstream speed $c - v$ as it plows its way against the ether flow and a boosted speed $c + v$ if it is directed downstream from the ether flow. This is just like a person swimming against and with a current in a river: watching the swimmer's progress from the bank, we would see the swimmer advancing more speedily in the second case than in the first.⁶

However, if light were directed perpendicular to the ether flow, it would not be retarded or boosted but just partake of the flow. Michelson and Morley arranged to have light travel in both the perpendicular and ether flow directions for equal distances and be reflected back to their origin, thus allowing the light to interfere in recombination.

Their experiment was not designed to measure the speed of light but rather to measure *differences* in light speed along different directions or paths. Under the assumption that the net speeds would differ in the different directions of travel through the ether, the light beams would constructively and destructively interfere with each other.⁷ Try as they could, they were never able to detect the expected effects of the interference that would be present, had the light been traveling through an ether wind. Following this effort, Lorentz and Fitzgerald had hypothesized that bodies somehow underwent a physical contraction in the direction of motion when they traveled through the ether and hence the path length would be altered in just the right amount to remove what would have been the effects of the interference. However, many viewed this as a contrived solution to the puzzle and as we view this idea today, the Lorentz-Fitzgerald rationale appears even more naïve. In more recent times, the equivalent of the Michelson-Morley experiment has been performed using lasers, enabling far greater accuracy and the null result continued to hold.

It took the genius of Einstein to see the apparent contradiction in a totally different light (if the pun may be excused). He reasoned that there is no ether and that light has the speed c whether one measures it in any direction relative to the motion of the earth in its orbit around the Sun. Einstein's bold hypothesis: *the speed of*

⁶ As an interesting extreme example, if the swimmer's speed relative to the river were the same as the speed of the river relative to the bank, for the observers on the bank the swimmer would appear to undergo no advancement at all when he swims upstream. His arms and legs would be flaying but he would be going nowhere relative to the observers on the river-bank!

⁷ To get a simple picture of constructive and destructive interference, consider how one "interferes" with the motion of a child on a swing in the playground. To provide (maximum) "constructive" interference, that is to make the swing go higher and higher, one provides a push on the swing at the point in each cycle when the swing is at its highest point, in phase with the motion. By contrast, one renders "destructive" interference when one provides a push when the swing is still in motion towards the position of the pusher, that is out of phase with the motion. The latter has the effect of damping the swing motion.

light in vacuum is always c . The combination of Newton's Principle of Relativity, that the dynamical laws of physics are the same in all inertial frames of reference plus Einstein's hypothesis of the universality of the speed of light and extending the equivalence of inertial frames to all physical laws is generally referred to as Einstein's Principle of Relativity. The additional constancy of c hypothesis forces dramatic changes in physical theory. While it becomes somewhat more palatable to accept his hypothesis in conjunction with the idea that light can propagate in the absence of any medium, it nevertheless remains counterintuitive. After all, suppose we return to the corpuscular or quantum picture of light: little balls of energy moving at speed c . If these "quanta" (recall that they are also called "photons" when referred to light) were instead a stream of baseballs moving at speed c , then even without a medium, if we were to run toward the balls with speed v , we would measure their speed as $c + v$ relative to us and if we were to run in the opposite direction, we would measure a speed $c - v$. Relative to our catching the balls when we stood still, there would be a greater sting in our baseball glove when running towards the direction of motion of the balls and a reduced sting in the opposite direction. It is a reflection of the different energies of motion. There is a corresponding effect with light that shows itself as a shift in frequency rather than in speed of the light quanta (photons).

The truly remarkable, totally counterintuitive character of light is that it always has the same speed c in vacuum, regardless of the motion of its source or the motion of the observer. We do not see it as "speeded up" by running towards its source as we do with baseballs. Now since it is an experimental fact that science has never measured anything other than light⁸ moving even at the speed c , let alone faster than c , and since we cannot boost the speed by running toward it when the speed in question is c , we conclude that according to Einstein, there is a "speed limit" for bodies and waves in nature, namely the speed c . The existence of this speed limit can also be appreciated from the fact that it would require an infinite amount of energy to bring a body of mass m to the speed of light, as we will see in Chap. 3.⁹

In turn, since all inertial reference frames are physically equivalent, that speed limit had better be the same in all the frames. It is understandable that many resisted Einstein's bold hypothesis when it was first proposed. Some of the consequences that derive from his hypothesis are even more astounding, as we shall explore in the coming chapters.

2.4 The Whole Electromagnetic Spectrum

We have discussed an essential feature of light but there is a much bigger picture to discuss. Electromagnetism is of great importance to physics in general and to Relativity as well as to our lives, of course. In what follows, we will take you through some of the basics, a very brief guided tour of the electromagnetic spectrum.

⁸ More generally, the family of electromagnetic waves, of which light is a member.

⁹ Whether this limit also applies to the speed at which information can be propagated becomes more involved in the strange world of quantum mechanics, as we will discuss later.

Light is just a small slice of the very broad electromagnetic spectrum with elements that you have heard about many times: radio waves, microwaves, infrared rays, ultraviolet rays, X-rays, and gamma-rays. The waves that allow us to see with our eyes, the light rays, fit into this list between the infrared and the ultraviolet rays. All electromagnetic waves are in the same family, composed in the same manner of oscillating electric and magnetic fields. They all travel at speed c in vacuum. The members are distinguished from each other by their wavelengths with the radio waves having the longest wavelengths (and therefore the lowest frequencies),¹⁰ and gamma-rays having the shortest wavelengths (and the highest frequencies).

While electromagnetic waves reach us from the Sun, the stars, the distant galaxies, the quasars, the pulsars and from the deepest recesses of space, we can (and do) produce them by our own actions and our modern technologies. At the simplest level of our everyday experience, we produce them when we strike a match. At the more fundamental level, we produce an electromagnetic wave when we wiggle (i.e. accelerate) a charge. Accelerated charges produce electromagnetic waves. Imagine the wave propagating outward from the accelerating charge at the speed of light. As we wiggle it faster and faster, we observe some interesting results.

Suppose for example, we were able to wiggle the charge at a frequency of 530–1700 kHz,¹¹ the wavelength would be up to 600 m long and we would produce noise on the AM radio. A typical AM radio has the following numbers on the dial: 530–1700 kHz. Now, if we were to shake the charge with a greater amplitude (while maintaining the same frequency), we would produce a louder sound on the radio. This process is called Amplitude Modulation or AM. We do not have any mechanical device to wiggle a charge that quickly. Instead, radio waves are typically produced by sending charges up and down a very tall antenna (100–200 m tall).

At a rate of oscillation of 88–108 MHz, we would produce noise on the FM radio. In FM broadcasting, the loudness of the sound is not controlled by the amplitude but by the frequency. For example, if we increase our “wiggle frequency” from 99.900 to 99.915 MHz, we would progress from a quiet sound to a loud sound. This varying of frequency is called frequency modulation or FM.

At 900 and 2400 MHz we enter the spectrum of cordless phones and “wifi” internet connection respectively. Cellphone signals reside at 800, 850 and 1900 MHz. VHF (very high frequency) signals have frequencies in the range 30–300 MHz and UHF (ultra-high frequency) signals span the range 300–3000 MHz for television broadcasting.

Microwaves reside at $3 \cdot 10^{11}$ – 10^{13} Hz or 300–30000 GHz. Producing microwaves by sending electrons up and down an antenna at such incredibly high frequencies is not physically possible. Instead, microwaves are generated by sending electrons around a warped circle within a vacuum tube called a magnetron. One can think of

¹⁰ Frequency, or cycles per second, with symbol ν is inversely proportional to wavelength with symbol λ and the product of the two is c , or in equation form, $\lambda\nu = c$. It can be seen as follows: λ is the advance in distance per cycle and ν is the cycle advance per second, hence the cycles cancel in the product leaving distance advance per second or velocity which is c .

¹¹ A kilohertz, kHz, is a thousand cycles (or wiggles) per second. A megahertz, MHz, is a million cycles per second. A gigahertz, GHz, is a billion cycles per second.

it as a particle accelerator. As the electrons weave through cavity, their oscillations emit microwaves.

Proceeding to higher frequencies, at the bottom end of the optical spectrum, in the region of $4 \cdot 10^{14}$ Hz, infrared and light of red colour are next to each other. At the higher end of the optical spectrum in the region of $8 \cdot 10^{14}$ Hz reside the colours blue, violet and the invisible ultraviolet rays. The energy quanta of each ultraviolet photon is much, much greater than, for example, the microwave photons. One can see the dramatic difference of effects produced by different types of photons in the “photoelectric” effect: if we shine red light (or microwaves) onto a metallic surface in a vacuum, no electrons would be ejected, no matter how many lamps we use. However, if we were to shine ultraviolet light onto the surface, no matter how dim, electrons would be ejected. This is a prime example of a quantum phenomenon.¹² At still higher frequencies, $10^{17} - 10^{20}$ Hz, we encounter X-rays. Beyond X-rays in the spectrum, we have gamma-rays at $10^{20} - 10^{24}$ Hz. We can only produce them using particle accelerators or observe them directly through nuclear decay in radioactive materials or as cosmic rays arriving on Earth from outer space.

There may be yet more powerful radiation but the most energetic phenomena that we have detected in the universe are gamma-ray bursts. These were discovered by military satellites in 1967 during the Cold War in the course of detecting nuclear weapons testing. Gamma-ray bursts are so powerful that if one were to occur within our galaxy, it could cause mass extinction on Earth. Fortunately, it is estimated that their frequency of occurrence within our galaxy is as low as one per million years and even if one were to occur within our galaxy, it is unlikely to be pointing directly at the Earth. Therefore we would not advise you to ask your insurance agent for gamma-ray-burst insurance.

¹² Einstein was awarded his one and only Nobel Prize for his explanation of the photoelectric effect. Many have argued that he should have been awarded at least three Nobel Prizes.

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