History

In the previous chapter we gave an introductory explanation as to why models play such a central role in contemporary science, and also alluded to the fact that without models there wouldn't be much science left to consider. In order to fully appreciate this deep connection between science and the practice of modelling it will be useful to view models from a historical perspective. This chapter will give an account of the historical development of the concept which stretches from the scientific revolution of the 17th century to the scientific inquiry of today. In order to fully appreciate this account we will also investigate the concept of a "mechanism", which since its inception into the natural philosophy of the 17th century has become a central term in modern science. Finally, we will look closer at an example from the history of Swedish science, namely the pioneering work of the engineer and scientist Christopher Polhem, and in particular his work on scale models.

It Started as an Analogy

The first steps towards the practice of modelling, as we know it today, were taken during the scientific revolution of the 17th and 18th centuries, a time when religious world-views based on Christian belief, and ideas from antiquity, were displaced by novel ideas based on observation and critical thinking. During this period of time the empirical scientific method, based on experience, was adopted by many scientists and natural philosophers, and paved the way for many scientific achievements such as the heliocentric worldview put forward by Copernicus, the laws of planetary motion first described by Kepler, and perhaps the most important, Newtonian mechanics. These advances were strongly coupled to a mathematical approach to mechanical phenomena, and even required the invention of new kinds of mathematics, such as the differential calculus. However, describing Nature in these novel mathematical terms required both abstraction and simplification. When Galileo, and later Newton, derived

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their laws of motion they made use of numerous simplifying assumptions, such as point masses and frictionless planes, which allowed for a mathematical treatment, but at the same time separated the analysed phenomenon from its real counterpart. They were both however well aware of the importance and ramifications of such simplifications, a fact which becomes clear in the following passage by Galileo which discusses the motion of falling bodies:

> As to the perturbation arising from the resistance of the medium this is more considerable and does not, on account of its manifold forms, submit to fixed laws and exact description.[1]

In the previous chapter we argued that mental models are the basis on top of which scientific ones are built, and even if this is the case, the abstraction enforced by mathematical tools and reasoning can be viewed as a first step towards the modern conception of a model. In order to describe mechanical phenomena in mathematical terms they had to be simplified to an appropriate level of description, at which stage the mathematical tools could be applied. This allowed for an accurate description of many phenomena, such as planetary motion, but the process of simplification itself also turned out to be a powerful (and general) tool that would help scientists to reach a deeper understanding of the natural world.

The school of thought which paved the way for many of the scientific achievements during this period is known as the mechanistic (or corpuscular) philosophy and among its proponents one could find philosophers such as René Descartes, Francis Bacon and Pierre Gassendi. The basic tenet of this philosophy was to view the entire universe as a machine, often in analogy with a mechanical clock.[2] Animals and plants were considered as mere machines made of flesh, and all natural phenomena were considered as explainable in terms of "micro-mechanical" actions. This was in stark contrast with the, at that time, dominating Aristotelian worldview where intention and purpose were the means by which Nature was to be explained. For example the force of gravity was, in the Aristotelian tradition, thought to emerge from material objects striving to reach their natural place in the universe. Man and in particular his soul was however excluded from the new mechanistic explanations, simply by placing them outside of the material world.[3]

The success that was achieved when mathematical and in particular mechanistic thinking was applied to classical mechanics, led to a rapid spread of this new way of investigating natural phenomena to other branches of physics such as optics and fluid dynamics,[4] that previously had been dominated by purely experimental work.

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[1] Galileo Galilei, *Discorsi e Dimostrazioni Matematiche, intorno a due nuove scienze* (1638).

[2] An example of this analogy is provided in the following quote by Kepler: "I am occupied with investigating the physical causes. The aim of this work is to show that the machine called the Universe does not resemble a deity but a clock".

[3] This famous move was carried out by René Descartes who in his book *Les passions de l'âme* (1649) claimed that man was made out of two distinct substances *res cogitans* (mental substance) and *res extensa* (corporeal or extended substance) and that the communication between the two occurs in the pineal gland of the brain.

[4] Important works of this time are Newton's *Opticks* (1704) and Daniel Bernoulli's *Hydrodynamica* (1738).

The development of sophisticated mathematics in conjunction with the mechanical philosophy lead to a formalisation of physics as a science. This change later became known as the "mathematisation" of physics and transformed a discipline dominated by experimental work into one where mathematics and formalism played an integral part, a trend which has persisted until today. An interesting consequence of this, which didn't become obvious until the beginning of the 20th century when quantum mechanics was formulated, was that certain branches of physics had become abstract and mathematical to such a degree that the topic of inquiry was incomprehensible without mathematics, and hence the differences between a mathematical model, pure mathematics and physics had become indistinguishable. An example of this is string theory, which describes the smallest constituents of matter, not as point-like particles, but instead as vibrating one-dimensional strings. This assumption is not based on any observational data, and the theory has not been able to provide predictions that are experimentally testable. One could therefore say that string theory exists somewhere in the twilight between mathematical fiction and physical reality.

When the use of mathematics during the 18th century spread from classical mechanics into other disciplines, one of the first disciplines to adopt this new way of thinking was electrical theory. This resulted among other things in the formulation of Coulomb's Law, which describes the forces between two electrically charged particles, and whose mathematical formulation is very similar to the equation postulated by Newton in order to describe the gravitational attraction between two bodies. Further, in the field of heat conduction Fourier made significant progress by applying mathematical techniques to the problem of heat flow in different materials. The fact that Fourier considered the flow of heat is interesting and illuminating, since the concept of "flow" is taken straight from mechanics; the change in heat distribution over time was considered in analogy with a liquid, which through its flow becomes evenly distributed in space over time. This analogy was later carried over to the concept of an electrical current, i.e. the flow of electrons through a conducting material. Both these descriptions of physical phenomena highlight the importance of analogies originating in classical mechanics when laws and later theories in thermodynamics and electromagnetism were discovered.

Possibly the most obvious example of the transfer of ideas and concepts from classical mechanics is Maxwell's derivation of the equations describing an electromagnetical field. In the modern exposition of electromagnetical field theory, electricity and magnetism are considered to be vector fields in space,[5] whose direction and magnitude depend on a set of so called partial differential equations. In teaching, these equations are presented without further motivation, and the focus lies instead on solving them in particular cases. But the equations weren't simply postulated by Maxwell, but in fact derived from a mechanical perspective, in which he considered the magnetic field as a fluid full of vortices whose rotation was proportional to the magnitude of the field. The fluid was assumed to be electrically charged and the fluid

[5] A vector field describes a quantity which at every point in space has both a magnitude and a direction, as opposed to a scalar quantity which only has a magnitude. For example *wind* is a vector field, while *temperature* is a scalar field.

flow which derived from the vortices gave rise to an electric current. Based on this analogy Maxwell could with the help of the laws of classical mechanics derive the properties of the magnetic field. The fact that the magnetic field in reality consisted of something other (exactly what was unclear) than an electrically charged fluid was beyond doubt, which can be seen from the following passage taken from Maxwell's seminal paper *On Faraday's Lines of Force* (1861):

> The substance here treated of must not be assumed to possess any of the properties of ordinary fluids except those of freedom of motion and resistance to compression. It is not even a hypothetical fluid which is introduced to explain the phenomena. It is merely a collection of imaginary properties which may be employed for establishing certain theorems in pure mathematics in a way intelligible to many minds[...]

This clearly illustrates how useful analogies and models can be in order to grasp and think about natural phenomena, which otherwise seem intangible. It is also worth mentioning that the modern exposition of electromagnetical field theory in terms of partial differential equations was formulated in the 1890s by Hertz, who incidentally was the first to verify the theory experimentally.[6]

Maxwell also contributed to the development of a completely different field in physics, the kinetic theory of gases, and also in this case with the aid of mechanical analogies. That gases consist of particles, and that the temperature of a gas depends on the velocity of the constituent particles was suggested by Clausius, who also identified the temperature as the mean velocity of the particles. By viewing the particles as inelastic bodies that, in analogy with billiard balls, exchange momentum upon collision, Maxwell was able to derive their distribution of velocities. This result was later refined by Boltzmann, and the distribution is today known as the Maxwell–Boltzmann distribution.

The general approach that the above examples highlight was to first represent a phenomenon in a mechanical fashion and then, based on that arrangement, derive a mathematical expression that links the variables (e.g. pressure and volume) that describe the system. The importance attributed to this method can be appreciated by considering the following quote from 1904 by Lord Kelvin, one of the greatest physicists of the 19th century:[7]

> It seems to me that the test of 'Do we or do we not understand a particular point in physics?' is 'Can we make a mechanical model of it?'

It is worth pointing out that the physicists of the 18th and 19th centuries did not believe that the world was made up only of fluids, pulleys and billiard balls, but that it could be described as if it was. Mechanical models and analogies were a means of representing and visualising relationships between different parts of physical systems, and this in conjunction with classical mechanics made it possible to derive mathematical descriptions of these systems.

[6] H. Hertz, *Untersuchungen über die Ausbreitung der elektrischen Kraft* (1893).

[7] Baltimore lectures on wave theory and molecular dynamics (1904). In: Kargon, R. and Achinstein, P. (ed.) (1987). Kelvin's Baltimore Lectures and Modern Theoretical Physics, MIT Press (1987).

Abstraction

During the early 20th century the mechanistic school of thought had to yield to a more abstract and mathematical approach to physics. In this period quantum mechanics, which describes the physics of the very small, emerged as a contender to classical Newtonian physics, which many believed could explain all aspects of the world and was close to being a complete theory. The emergence of quantum mechanics effectively up rooted that belief and also turned out to be essentially different from classical mechanics. The predictions made by this new theory were not solid and deterministic statements, but only given in terms of probabilities. This indeterminism left little room for understanding the theory in terms of everyday mechanical analogies, and the contemporary relativity theory with its four-dimensional curved space-time was also difficult to grasp from an intuitive mechanical perspective. This displacement from the mechanical to the abstract and mathematical was summed up in 1937 by the philosopher of science Philipp Frank when he wrote:[8] “The world is no longer a machine but a mathematical formula”.

In the work of many physicists emphasis was slowly shifting from analogies to theories and abstract models, and the former were considered to be lower rank, half-done theories that were only useful as tools for reaching a complete theory. A contributing cause to this was the unity of science movement within philosophy of science that advocated a rigorous unification of all the sciences. In this grand plan there was no room for small models of isolated phenomena, even less so for several distinct models of the same phenomena. Discovery driven by analogies, also known as the intuitive-transductive method, was challenged by the hypothetical-deductive method, inspired by contemporary trends in mathematics that strived for axiomatisation and formalisation.[9] The basic tenet of the latter method was to mathematically deduce experimentally testable predictions from a small number of assumptions or axioms about the phenomenon. This was however a highly set goal that, except in a few cases such as Fresnel’s deduction of optical patterns of diffraction, was seldom realised[10] and mostly existed in the minds of philosophers of science. The limits of our knowledge are in general advanced by hypotheses and educated guesswork, rarely through grand derivations or deductions.

[8]The mechanical versus the mathematical conception of nature, 1937, Philosophy of Science 4: 41–74.

[9]This trend was most clearly expressed by the French Bourbaki group who published a series of nine books on different aspects of mathematics in which everything was solidly founded on set theory. The books were all published under the pseudonym Nicolas Bourbaki.

[10]Fresnel, A. (1818). Le diffraction de la lumière.

Followers

The other branches of science soon continued in the footsteps of physics. Chemistry followed a similar mathematical and abstract route, while other disciplines adopted the mechanistic thinking of physics without being able to adapt and apply mathematics to the same extent. A general trend that can be traced in the history of science is a transition from an aspiration to describe *how* the world is constituted to a desire to explain *why* this is the case. We want to know both how the world is constituted and why this is so. An explicit, albeit heavily simplified, example of this is the transition that biology went through in the 19th century. Linnaeus, who introduced the notion of a formal classification into biology, catalogued and classified animals and plants into different species, families and other taxa. Since it was considered that all plants and animals were created by God and forever fixed, there was no impetus to explain why a certain species existed in a given location or why it had certain characteristics. All this changed when Darwin, during the second half of the 19th century, discovered that novel species are created and shaped by evolution through natural selection. Biology changed from a discipline concerned only with classification to one which tried to explain why the organic world is structured the way it is. Darwin established the basic mechanisms necessary for evolution to take place: heredity, variation and natural selection, and argued that these mechanisms were sufficient to explain all aspects of biology.

Another branch of science that underwent drastic changes during the 19th century was medicine, which went from a fairly non-empirical discipline, based on vague, often untested assumptions about the human body, such as humorism,[11] to a quantitative discipline that strived to established empirical well-founded causes. An example of this is the discovery, made during the second part of the 19th century, that it is microbes, such as bacteria and viruses, that cause contagious diseases. The microbes thus were the mechanism by which diseases could be transferred from infected to healthy people, and with this knowledge it became easier to explain how diseases spread and also to contain outbreaks. Mathematical approaches have also been successful in medicine, and one example of this, related to contagious diseases, is the application of mathematical modelling to the spread of cholera in Soho during the Victorian era.[12]

After these two specific examples let us take a step back and think about the way in which explanations of almost all natural phenomena have changed over time. During the course of history, humans have always put forward explanations as to why the world looks the way it does. Initially these explanations were of a religious nature, but as time has passed scientific explanations have become increasingly common. But where in this chronology do models fit? When did models become commonplace in scientific explanations? A comprehensive answer to these questions requires a historical study that is far beyond the scope of this book. However, the latter question

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[11] This theory states that the human body consists of four different substances: blood, phlegm, yellow bile and black bile, and that imbalances in these cause disease.

[12] Körner, T. (1996). The Pleasures of Counting, Cambridge University Press.

hints at a transition between different attitudes towards reality. How do simple models and simple explanations, such as humorism, really differ? An explanation that is based on a model is a *simplification*, which, despite the fact that it neglects many aspects of reality, provides a satisfactory answer, while a simple explanation assumes that the world in itself is simple. Humorism postulated that the human body only consisted of four distinct elements, not that the body acted as if it was that simple. Theories, be they simple or complicated, have a claim to truth, while models are constructed out of simplified and false premises. In other words, the two types of explanations differ because there is a fundamental difference between claiming that something is simple, and claiming that it can be explained in a simple way. Many complex systems are governed by surprisingly simple principles, and these are made use of when building models of these systems. Creating a model and using it in order to explain a certain natural phenomenon can be viewed as conceding its complexity, and the emergence of models in scientific practice can therefore be said to coincide with this insight. The world is immensely complex, but at least we can understand small parts of it.

Mechanisms

Previously in this chapter we have discussed the idea of "the world as a machine" and applications of this idea in terms of mechanistic explanations of natural phenomena. This method was first applied in physics (or rather classical mechanics) and has from there spread to other branches of science, and today it is difficult to imagine any kind of science that does not provide its explanations in terms of mechanisms. But what do we actually mean by the concept "mechanism"?

The exact meaning of the concept is difficult to pinpoint, the main reason being that it is used by so many disciplines in many different contexts, but a common feature is that it is used when one tries to explain an often complicated phenomenon in terms of simpler steps of interacting components. The crucial thing is that the system that exhibits or gives rise to the phenomenon consists of different parts and that these parts influence each other in a systematic and predictable manner. The mechanism is realised by a collection of objects, each with its own distinct properties, that interact with one another through a set of activities, and these interactions change the properties of the objects in such a way that the phenomenon comes about.[13]

In order to clarify this somewhat abstract reasoning we shall present a few mechanistic examples from two distinct disciplines, molecular biology and economics.

In all living cells proteins are being produced, and the structure of each protein, and therefore its function, is determined by a particular stretch of the genetic code, the DNA. The protein is however not produced directly from the DNA sequence but via a number of intermediary steps: initially the DNA is transcribed into messenger

[13]Machamer, P., Darden, L. and Craver, C.F. (2000). Thinking about mechanisms. Philosophy of Science 67:1.

RNA that is transported to the ribosomes outside the nucleus, where it is translated into a chain of linked amino acids that finally folds into the protein. This is a severe simplification of the actual sequence of events, which is highly complex and affected by a large number of additional factors, but at least this description gives an indication as to what a mechanistic explanation in molecular biology might look like.

The relation between interest, inflation and unemployment rate is commonly explained in the following terms: If the unemployment rate is lowered in a society then the total purchasing power is increased. This implies that the value of money is reduced and leads to an increase in inflation. On the other hand, the interest rate influences both inflation (higher interest rate implies less borrowed money, which increases the value of money and reduces inflation) and unemployment rate (lower interest rate leads to fewer investments and hence fewer jobs).

What we take as a mechanism depends on what we view as fundamental in our description of a system. Initially mechanisms were exactly what you would expect from the name, since mechanical activities (forces, torques etc.) and macroscopic objects, which could be idealised into levers or inclined planes, were the only ones known to the scientists of the 18th century. As more objects (cells, molecules, atoms) and activities (diffusion, exchange of electrons, enzymatic activity) have been discovered these have been added to the list of possible mechanisms. What we view as fundamental often depends on the scientific discipline we belong to. A molecular biologist can for example say the following concerning the function of a molecule:[14]

> Inositol triphosphate is a hydrophilic molecule and moves in the cytoplasm. This messenger works by mobilizing calcium from calcium stores in the endoplasmic reticulum. It does so by binding to a receptor and opening up a calcium ion channel. Once the ion channel is open, calcium ions flood the cell and activate calcium dependent protein kinases...

In this case we can identify molecules binding, opening and cleaving as the mechanisms at work. Chemists usually make use of more fundamental or lower level mechanisms, as in the following example that describes how an alcohol is dehydrated in the presence of an acid and a water molecule is produced:[15]

> The reaction begins with a Lewis acid–Lewis base reaction between a hydrogen ion from sulfuric acid and a nonbonding electron pair on the alcohol: an oxonium ion results. The oxonium ion loses a water molecule to form a carbocation. In the final step, the carbocation is neutralized by elimination of a hydrogen ion with the resultant formation of a carbon–carbon double bond.

In this example the mechanisms act at the level of single electrons, atoms and molecules, and result in the neutralisation and creation of chemical bonds.

These four examples from molecular biology, chemistry and economics illustrate how the behaviour of a system can be broken down into interactions between subsystems that together give rise to the dynamics of the whole system. To a certain degree these explanations can be viewed as models in themselves, since they

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[14] Patrick G.L. (2001). An introduction to medicinal chemistry, Oxford University Press.

[15] Bailey, P.S. and Bailey, C.A. (2000). Organic Chemistry: A brief survey of concepts and applications, Prentice Hall.

give a simplified and idealised picture of the true course of events, but importantly this reduction of the phenomenon implies that it in a natural way can be translated into mathematical terms. A system whose behaviour is driven by mechanisms can be modelled, whether the mechanisms are of a "classical mechanics" type (billiard balls etc.) or of more recent kind (chemical reactions, diffusion etc.). The dynamics of the system can be described either verbally (as above), graphically as a flow chart or quantitatively with one or more mathematical equations.

Christopher Polhem—A Modelling Pioneer

We will now take a leap back in history and focus on one of the pioneers of Swedish science and, in particular, modelling.[16] Christopher Polhem was active during the first half of the 18th century. He worked as an engineer, inventor and scientist, and is considered one of the most prolific scientists to have ever lived. Polhem was first and foremost interested in practical things, such as identifying and solving technical problems in mining, transport and handicrafts. These tasks suited him very well, since he was equipped with a well-developed sense of space, and had an intuition for mechanics that could be matched by none. In his youth, with the support of a stipend from the Swedish Board of Mines, he travelled around Europe for five years. The purpose of the trip was both to educate the young Swede, and, in a form of industrial espionage, to acquire knowledge about technical novelties and innovations, such as mills, saw mills, and locks. Without making a single drawing during his trip he could, upon his return to Sweden, reconstruct several machines simply from memory.

Although Polhem had an excellent intuition for mechanical construction he was not alien to the idea of systematically investigating his inventions to see if there was any room for improvements. In order to achieve this he made use of miniature scale models that he collected at his *Laboratorium mechanicum* in Stockholm. It was a place intended as a source of inspiration for other engineers and inventors, but also had an educational purpose, where students could learn basic mechanics in a concrete manner. The most famous of Polhem's model constructions is the "hydrodynamical experimental machine" that was built in order to investigate the efficiency of different water wheels. By letting water flow through the wheel for exactly one minute, and at the same time measuring the velocity of the wheel, the efficiency of the design could be estimated. The construction contained five parameters that could be adjusted independently: the shape of the shovels, the ratio between the diameter of the water wheel and the crank, the drop of the water, the angle of the water inlet and finally the load put on the wheel. By systematically varying these parameters in repeated experiments (it has been estimated that 20,000–30,000 experiments were carried out during two years) Polhem tried to find the parameter setting that yielded maximal power (energy per unit time) as a function of the wheel load. This is most likely

[16]David Dunér (2009). Modeller av verkligheten. Modellbyggaren Polhem, seendet och det spatiala tänkandet, Vetenskapssocieteten i Lund, Årsbok.

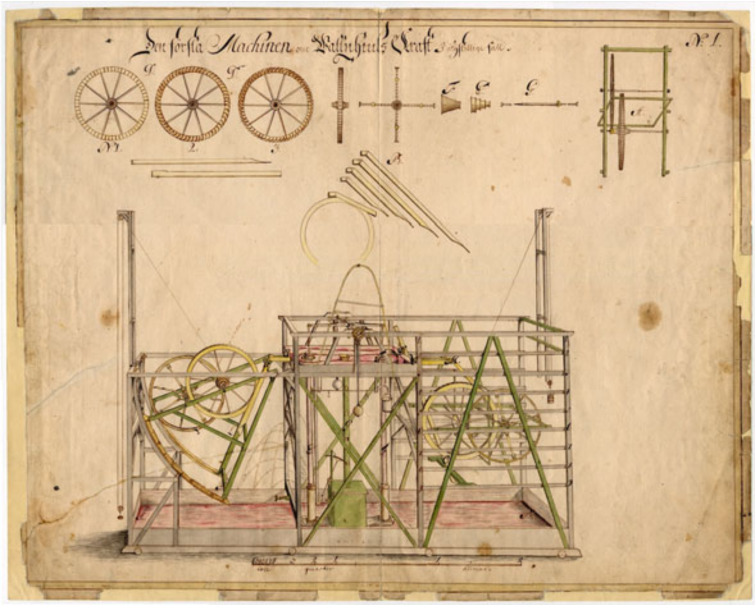

Fig. 1 A drawing of Christopher Polhem's "Hydrodynamic experimental machine". *Source* The library of the Royal Institute of Technology, KTH, Stockholm

the first documented case of optimisation through parameter variation, a technique that today is common, and is often used in the context of mathematical models and computer simulations.

A curious story related to the hydrodynamical experimental machine concerns a former student of Polhem's, Per Elvius Jr., who also tried to optimise the construction, but this time with the help of classical mechanics. With the aid of Newton's laws of motion and mathematical deduction, Elvius tried to find the most efficient construction without actually carrying out a single experiment. Interestingly he was strongly discouraged to try this by Polhem himself—a distinct clash between practical and mathematical modelling.

Polhem was also the first engineer to suggest that experiments with scale models of ships in a flume could be used in order to investigate how the shape of the hull affects the water resistance of a ship. We know today that he was well aware of the problems that appear when scale models are utilised,[17] but most likely he was ignorant of the complicated scaling that one needs to take into account when modelling the flow of

[17]The problem of scaling is best illustrated by looking at how the surface area and mass of a model changes as the size of the model increases, a relation which is of major importance when building e.g. prototypes of airplanes. The volume and therefore mass will increase as the length to the third power (if the length is doubled the mass increases eight-fold) while the surface area of the wings and hence the force lifting the plane only increases as the square of the length (and only quadruples when the length is doubled).

water (see p. 89). He did however not conduct any quantitative studies, but instead focused on the qualitative impact of the design of the hull on the properties of the ship. For example he tried “either a pointed, broad, flat, hyperbolic or parabolic hull and a high, low, pointed or broad bow”. The actual experiments were not carried out by Polhem, but by his assistant Emanuel Swedenborg, who today is at least as well known as his teacher.

The use of scale models, to let the large be represented by the small, and the idea that the same laws apply to both is something that we today take for granted, but this was far from obvious for the contemporaries of Polhem. His achievements in engineering and his use of scale models makes him a pioneer of scientific modelling and his research paved the way for the modern use of models (Fig. 1).

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