Chapter 10
Mechanistic Explanations in Physics: History, Scope, and Limits

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Abstract Despite the scientific revolutions of the twentieth century, mechanistic explanations show a striking methodological continuity from early modern science to current scientific practice. They are rooted in the traditional method of analysis and synthesis, which was the background of Galileo's resolutive-compositive method and Newton's method of deduction from the phenomena. In early modern science as well as in current scientific practice, analysis aims at tracking back from the phenomena to the principles, i.e., from wholes to parts, and from effects to causes. Vice versa, synthesis aims at explaining the phenomena from the parts and their interactions. Today, mechanistic explanations are atomistic in a generalized sense. They have in common to explain higher-level phenomena in terms of lower-level components and their causal actions or activities. In quantum physics, the lower-level components are subatomic particles, and the causes are their quantum interactions. After the quantum revolution, the approach continues to work in terms of the sum rules which hold for conserved properties of the parts and the whole. My paper focuses on the successes and limitations of this approach, with a side glance at the recent generalization of mechanistic explanations in cognitive neuroscience.

Keywords Mechanistic explanation · Method of analysis and synthesis · Resolutive-compositive method · Aristotelian tradition · Atomism · Conserved properties · Cognitive neuroscience

10.1 Introduction

The successes of natural science are based on the experimental method and the mathematical models of Galileo's and Newton's physics. Closely related to the foundation of modern physics was the mechanistic world view, according to which all material bodies were conceived to consist of mechanical corpuscles or atoms and

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to obey the laws of classical mechanics. Mechanistic thinking dominated the understanding of nature until the end of the nineteenth century, but with the advent of modern atomic physics, it became apparent that a mechanistic understanding of nature in terms of classical physics was incompatible with the atomistic structure of matter and the interactions of subatomic particles. Hence, the mechanistic approach to nature was generalised in twentieth century physics, chemistry, biology, and the investigation of neuronal mechanisms in neuroscience.

However, we should be careful about what "mechanistic" still means today. In the philosophy of biology and neurobiology, the roots of mechanistic explanations in early modern science and their scope in current scientific practice are usually not discussed. In view of the successes of cognitive neuroscience, it has been claimed that a complete scientific explanation of the world, including human consciousness, is in principle possible. Several neuroscientists and philosophers supported a deterministic world view according to which the human mind reduces to the neural mechanisms in the neocortex and free will is an illusion generated by the brain (Churchland, 1995; Roth, 2003; Singer, 2003, 2004; Rubia, 2009). In Germany, this view gave rise to a heated public debate, to the point of calling for changes in criminal law (Geyer, 2004). In the last decade, it became clearer that the human brain is tremendously complex and that the mechanistic explanations of neuroscience are not as far-reaching as expected. Hence it is time to take a step back and clarify their meaning and scope.

Despite the scientific revolutions of the twentieth century, mechanistic explanations show a striking methodological continuity from early modern science to current scientific practice. They are rooted in the traditional method of analysis and synthesis, which was the background of Galileo's resolutive-compositive method and Newton's method of deduction from the phenomena. In early modern science as well as in current scientific practice, analysis aims at tracking back from the phenomena to the principles, i.e., from wholes to parts, and from effects to causes. Vice versa, synthesis aims at explaining the phenomena from the parts and their interactions. Today, many mechanistic explanations are atomistic in a generalized sense. They have in common to explain higher-level phenomena in terms of lower-level components and their causal actions or activities. In quantum physics, the lower-level components are subatomic particles, and the causes are their quantum interactions. After the quantum revolution, the approach continues to work in terms of the sum rules which hold for conserved properties of the parts and the whole. My paper focuses on the successes and limitations of this approach, with a side glance at the recent generalization of mechanistic explanations in cognitive neuroscience.

10.2 The Origin of Mechanistic Explanations

The philosophical background of mechanistic explanations is the mechanistic world view of early modern science and philosophy, according to which all natural processes were considered as mechanisms, or to function like machines. The proponents of this world view were Descartes and Hobbes, regardless of their profound philosophical differences concerning dualism or materialism. However, the mechanistic world view is much older. The founders of early modern science and philosophy took up ancient atomism. Another crucial mechanistic paradigm was to compare the solar system with a clock, as illustrated by the famous astronomical clocks in European cathedrals since the Late Middle Age. Indeed, important mechanical explanations in early modern science relied on the analogy between the universe and a clock. Later, the laws of Newton's mechanics explained the dynamic structure of the celestial clock, or the machinery of the universe, in terms of gravitation as a universal force.

In general, a mechanism is a causal structure, or more precisely, a system of elements that work together to bring about or cause a process. The English term 'mechanism' derives from the Greek word μηχανή for 'machine' and the corresponding Latin word *mechanica* or its derivatives. A British dictionary defines a mechanism primarily as "1. a system or structure of moving parts that performs some function, especially in a machine" (Collins, 2012). A simple example of a mechanism is a clock. The system of elements is the clock. Its causal elements are the balance and the gears, which interlock in such a way that they move the clock hands to indicate the time on the dial (Fig. 10.1).

A mechanistic explanation, then, explains a phenomenon or process by a mechanism, i.e., in terms of certain causal elements or components that work together like the parts of a machine. The above dictionary extends the explication of a mechanism to this analogous use and gives a second definition, according to which a mechanism is "2. something resembling a machine in the arrangement and working of its parts: the mechanism of the ear" (Collins, 2012). This second, analogical meaning of the term 'mechanism' and its extension to the way in which organs function also emerged in the seventeenth century and dates to ancient atomism. Even Aristotle discussed the analogy between technical tools or machines and the processes of nature (Aristotle, *Physics*, 199a), albeit within his anti-atomistic, teleological account of nature. Early modern science dispensed with Aristotle's teleological explanations of mechanical processes to explain vice versa the way in which organs function in mechanical terms. In the Renaissance,

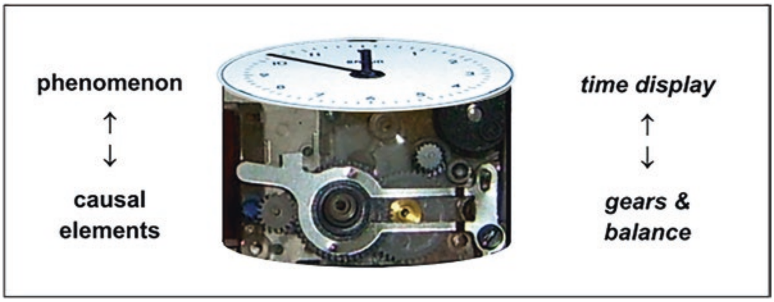

Fig. 10.1 The clock, a simple mechanism

mechanical analogies entered medical science. The title of Andreas Vesalius' famous anatomy textbook *De humani corporis fabrica* (Vesalius, 1543) paradigmatically expresses the analogy between the structure of the human body and an artificial structure. After the reception of the Arabian theory of vision in the Late Middle Age, and the rediscovery of ancient atomism as described by Lucretius (1570), early modern science started to develop mechanistic explanations of sensory perception (Hobbes, 1655).

10.2.1 The Tradition of Analysis and Synthesis

The mechanistic explanations of early modern science and philosophy were grounded in the ancient method of analysis and synthesis, an inductive method which has remained influential up to current scientific practice. It gives rise to a generalized mechanistic methodology, which is typical of the "dissecting" sciences (Schurz, 2014, 35) from Galileo's and Newton's days to recent neuroscience. The Greek terms *analysis* and *synthesis* mean "decomposition" and "composition" respectively. Today, exactly this meaning is still found in the practice of chemical analysis and synthesis. However, the traditional analytic-synthetic method of the exact sciences is much more complex. In the accounts of Galileo or Newton, analysis combines *decomposition* and *causal analysis*, whereas synthesis vice versa combines (re-) *composition* and *causal explanation*.

If we look at the typical structure of a mechanism (Fig. 10.2), we see that the analysis proceeds *top-down* from the whole to its parts, from the phenomenon or process to be explained down to the entities and interactions that compose it. The synthesis runs vice versa; it proceeds *bottom-up* from the parts and their interactions to the whole and from these entities and interactions as the *explanans* to the phenomenon or process *explanandum*. In modern philosophy, the analysis is inductive (or abductive). It gives rise to an inference to the causal structure that underlies a

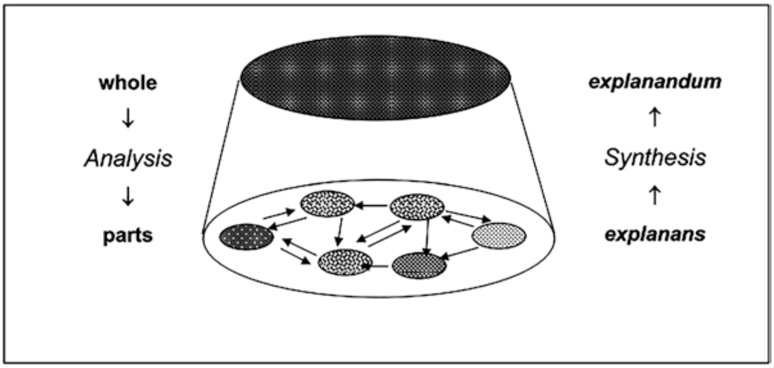

Fig. 10.2 Typical structure of a mechanism

phenomenon, i.e., it aims at an interference to the best explanation. The synthesis is then the corresponding mechanistic explanation of the phenomenon in terms of lower-level causal entities.

The method of analysis and synthesis traces back to ancient geometry and medicine, and it was widely shared in early modern science and philosophy (for details, cf. Beaney, 2021). However, there were two different methodological traditions of analysis and synthesis which merged in early modern science. On the one hand, the Aristotelian tradition of Latin medieval science and philosophy developed a resolutive-compositive method, *resolutio* and *compositio* being the Latin terms for *analysis* and *synthesis*. The medieval resolutive-compositive method combined inductive and deductive elements of reasoning. It remained attached to Aristotle's conception of induction and deduction and proceeded in terms of the logical connections between antecedents and consequences. In empirical science, these logical relations became associated with relations of cause and effect. Hence, the resolutive part of the method was the regress to causes, whereas the compositive part was a causal explanation. In the thirteenth century, this method was advanced by Robert Grosseteste, and later, in the Padua school of early modern science, by Giacomo Zabarella. Their method resembled Galileo's methodology (Crombie, 1953), but they still adhered the Aristotelian tradition of rejecting any mathematical analysis of the phenomena (Engfer, 1982, 95; Hintikka & Remes, 1974, 107–108).

On the other hand, there was the analytic-synthetic method of ancient geometry explained in Pappus's commentary on Euclid's works. In medieval science and philosophy, it was not available for a long time. Via the Arabic tradition, Pappus's method partially received in geometrical optics. Alhazen's Book of Optics (*De Aspectibus or Perspectiva*) was translated into Latin around 1200. Witelo's influential *Perspectiva* written around 1270 built on it (Lindberg, 1971, 1976; Crombie, 1953) and it refers to some proofs and geometrical constructions that seem to stem from a Latin partial translation of Pappus's commentary (Unguru, 1974). Pappus's complete Greek text and its Latin translation became only generally accessible in the Renaissance (Pappus, 1589; translation: Hintikka & Remes, 1974, 8–9). Then, it became very influential in the mathematical tradition of early modern science and philosophy.

Pappus's method of geometry was an inductive procedure that substantially differs from induction in the Aristotelian sense. For Pappus, analysis and synthesis were the complementary parts or steps of a joint regressive-progressive method. Its "analytic" part is regressive, it infers from something that is taken for given to an underlying first principle by running through the antecedents of this given (or assumed) consequence (Hintikka & Remes, 1974, 11–14). Its second, "synthetic" part is progressive or deductive. It aims at confirming the principles established by analysis by deriving from them what was originally given or assumed, i.e., by proceeding from the principle found by analysis to its consequences. So far it resembled the resolutive-compositive method of the medieval Aristotelian tradition, however, with two crucial differences: *first*, the inferences from consequences to antecedents or vice versa employed geometrical constructions; *second*, analysis was only the first part of the method, which was to be completed by synthesis.

In contrast to their medieval predecessors, Galileo and Newton used geometrical constructions to analyse the phenomena into their causal components, resorting to Pappus's account of analysis and synthesis and distinguishing their new science in this way substantially against the earlier scientific traditions. In addition, however, they adopted the causal aspect of the medieval resolutive-compositive method of the Aristotelian tradition. Their mathematical and experimental analysis of the phenomena into idealized components came along with causal analysis. Both reinterpreted the logical relations of antecedents and consequences of the resolutive-compositive method in terms of physical causes and effects; and they combined these causal relations with a mathematical analysis of the phenomena into components, which then are investigated by the experimental method. The resulting combined method of analysis and synthesis establishes a complex pattern of part-whole relations and causal relations. The causal structure of this complex pattern is investigated by mathematical and experimental analysis. This combined analytic-synthetic method and its application in experiments serves to analyse, explain, and predict natural phenomena in mathematical terms. Such a complex pattern of part-whole relations and causal relations is indeed typical of natural science up to the present day, and it corresponds to the structure of the mechanistic explanations on which recent philosophy of science focuses.

10.2.2 Newton's Methodology

Galileo did not explain his resolutive-compositive method in philosophical terms, but he practised it in his famous experiments with the inclined plane, in which he changed the inclination to analyse the causal components of the falling motion (Losee, 1993). Newton's main works, however, contain several methodological considerations. Roger Cotes relied on them in the preface to the second edition of Newton's *Principia,* where he stated that natural science proceeds.

> according to a twofold method, the analytical and the synthetic. They derive the forces of nature and their simple laws from a few selected phenomena by means of analysis, and present the former, by means of synthesis, as the nature of the remaining phenomena. (Cotes, 1713, 386).

This remark is very similar to Newton's account of the analytic-synthetic method in *Query 31* of the *Opticks*. There, he compares the method of natural science to the corresponding method of mathematics. Following Pappus, he emphasizes that the analysis or decomposition has always to be performed before the synthesis or composition:

> As in Mathematicks, so in Natural Philosophy, the Investigation of Difficult Things by the Method of Analysis, ought ever to precede the Method of Composition. (Newton, 1730, 404)

Then, he emphasizes that in physics the method of analysis and synthesis establishes part-whole relations and causal relations. In this way, he brings Pappus's geometrical method together with the Aristotelian tradition of the resolutive-compositive method and reinterprets the latter in terms of physical causes and effects. The analysis proceeds from phenomena to their components and causes; the effects in nature are motions; their analysis aims at finding the forces that cause them. The synthesis, conversely, serves to prove that these causes can indeed explain the phenomena:

> By this way of Analysis we may proceed from Compounds to Ingredients, from Effects to their Causes, and from Motions to the Forces producing them; and in general, from Effects to their Causes, and from particular Causes to more general ones, till the Argument end in the most general. This is the Method of Analysis: And the Method of Synthesis in assuming the Causes discover'd, and establish'd as Principles, and by them explaining the Phaenomena proceeding from them, and proving the Explanations. (Newton, 1730, 404).

These remarks on the analytic-synthetic method in the *Opticks* and the rules of philosophizing in the *Principia* point to the same method of "deduction from the phenomena" (Achinstein, 1991, 32–50; Worrall, 2000). At the beginning of *Book III* of the *Principia*, Newton gives four methodological rules to explain the analytic method (Newton, 1726, 794–796). The first two refer to the causal analysis of phenomena. They demand that no more causes be assumed than are sufficient to explain the phenomena, and that similar effects be attributed to similar causes. The third is a rule of induction, which demands to generalise the empirically known mechanical properties of bodies to *all bodies,* including the smallest constituents of bodies, i.e., the atoms, which Newton thought to exist. The fourth rule demands that empirically established hypotheses be maintained unless they are falsified, instead of considering contrary speculative hypotheses. This rule expresses a pragmatic conservativism concerning well-established theories. It not only conforms to Newton's famous dictum *hypotheses non fingo* (Newton …), but also to the following remark in his *Opticks*:

> This analysis consists in drawing general conclusions from experiments and observations by induction, and in admitting no objections to them which are not taken from experiments or from other certain truths. For hypotheses are not considered in the experimental study of nature. (Newton, 1730, 404).

Hence, analysis in Newton's sense combines the dissection of phenomena into components or of bodies into their constituent parts (third rule) with causal analysis (first and second rule). For the conclusions drawn from the phenomena, experimental observations are the touchstone (fourth rule and the passage just quoted). In the *Principia*, Newton shows that the analysis of the phenomena according to his rules of philosophizing gives rise to an explanation of the trajectory of thrown mechanical bodies on earth and the motions of celestial bodies in terms of one and the same cause, gravitation. A diagram in the appendix to the *Principia* demonstrates that there is a continuous transition from Galileo's parabola of the motion of a thrown body to the Kepler orbit of the moon around the earth, in accordance with Newton's first and second rules (Newton, 1729, 551; Fig. 10.3).

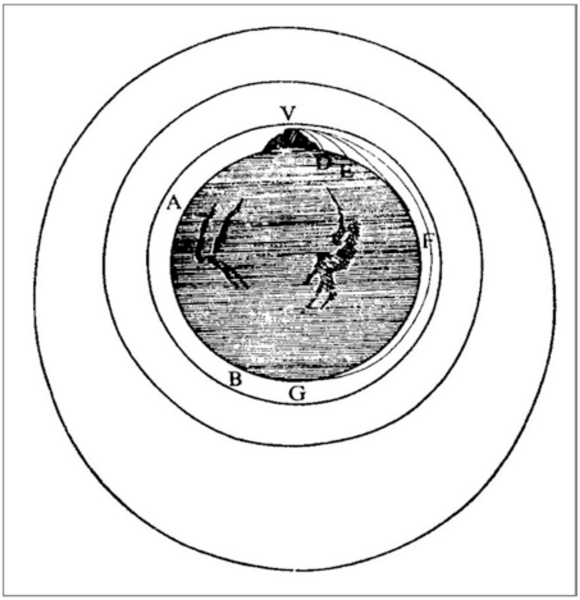

Fig. 10.3 Transition from Galileo's to Keplerian motion (Newton, 1729, 551)

The rules of philosophizing correspond to the analytic step of the analytic-synthetic method, while the axiomatic approach of the *Principia* in terms of definitions, laws of motions, and mathematical deductions corresponds to the synthetic step. The synthesis is the mathematical deduction of the motions from the law of force and gravitation. Only the latter step corresponds to the deductive-nomological (DN-) account of scientific explanation which dominated the philosophy of science for such a long time. For the *Opticks*, no such synthetic step from the principles of an atomistic theory of light to a deduction of the optical phenomena in terms of a mechanistic explanation was available to Newton. Here, he demonstrated the interplay of analysis and synthesis only by the experimental decomposition of white light into the spectral colours and by the opposite composition of white light from the coloured light rays by the superposition of two spectra of prisms arranged in parallel, which in turn yield white light (Fig. 10.4).

In Newton's days the axiomatic, or synthetic, approach corresponding to DN-explanations only worked for mechanics as a full-fledged mathematical theory of gravitation and the mechanical motions of bodies. But it did not work for Newton's optics. In this field, Newton was not able to support his analytic inference to light atoms as the best explanation of the phenomena discussed in the *Queries* of the *Opticks* by an atomistic theory of matter and light. Such a theory was not only beyond the scope of Newton's optics, but also of nineteenth century physics. With the rise of quantum theory, it turned out that mechanistic explanations based on the laws of classical physics cannot cope with the atomistic structure of light and matter.

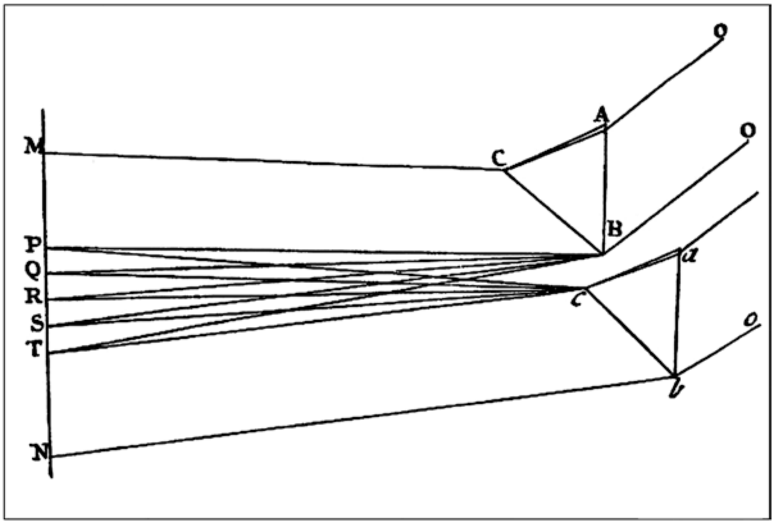

Fig. 10.4 Analysis and synthesis of light (Newton, 1730, 147)

10.3 Mechanistic Explanations Today

In twentieth century physics and beyond, mechanistic explanations were generalized in an inflationary way. To talk of mechanisms is ubiquitous in science and technology today. One speaks of the mechanism of the steam engine, the mechanism of signal transmission through light or radio waves, the electrodynamic and thermic mechanisms of the formation of a thunderstorm, the astrophysical mechanisms of generating cosmic rays, etc., and even the Higgs mechanism of the standard model of particle physics that explains the mass of subatomic particles. Examples from biology are the mechanisms of photosynthesis, of the replication of DNA, or of gene expression. We may add examples from neuroscience, above all the neural mechanisms that explain pattern recognition and learning by neural networks. In all these cases (except the Higgs mechanism, I suspect), these mechanisms explain a certain phenomenon or process in terms of part-whole relations and causal relations. Combining part-whole relations and causal relations, they retain the crucial features of the mechanical explanations of early modern science, i.e., they reproduce the inferential and explanatory structure of Galileo's or Newton's analytic-synthetic method. In addition, the mechanisms on which they rely still draw on the old analogy between processes in nature and the mechanisms of machines. The mechanisms of the steam engine, the formation of a thunderstorm, the generation of cosmic rays, photosynthesis, DNA reduplication, etc., including neural mechanisms, all have in common that they produce a phenomenon or process by their moving parts, or, generally, by the dynamics of their elements.

10.3.1 The Recent Philosophical Definitions

At this point we may look at the definitions of a mechanism in recent philosophy of science. The proponents of the recent “mechanistic turn” in the philosophy of science emphasize this dynamic aspect, but in quite different regards. Wesley Salmon and Stuart S, Glennan define the concept of mechanism in terms of causal processes or causal laws, having the laws of twentieth century physics in mind. Salmon (1984, 240) emphasizes that an adequate account of scientific explanation requires mechanistic explanations in a generalized sense and that they may even employ fields (ibid., 241). According to him, a mechanism is any causal fork or causal process, including stochastic processes:

> The theory here proposed appeals to causal forks and causal processes; these are, if I am right, the mechanisms of causal production and causal propagation that operate in our universe. These mechanisms […] may operate in ineluctably stochastic ways. (ibid., 239).

Hence, Salmon identifies mechanistic explanations and causal explanations. In his 1984 book *Scientific Explanation and the Causal Structure of the World*, he defined causal processes in terms of mark transmission, but later, in terms of the transmission of a conserved quantity between two events (Salmon, 1997). According to both definitions, the paradigm case of a causal process is signal transmission in physics, such as the emission, propagation, and detection of radio waves or light signals, including quantum processes such as the emission, propagation, and absorption of photons. This conception of a mechanism is very general. It holds for the classical impact of two billiard balls as well as for the transmission of a quantum signal, which obeys the principle of energy conservation and the probabilistic laws of a quantum theory. In addition, it is very basic. Signal transmission is a causal process that propagates from cause A to effect B, where A and B belong to one-and-the same level of phenomena. The part-whole relations, which are crucial for Newton’s analytic-synthetic method and the mechanistic explanations of early modern science, are missing here. According to Glennan, this approach indeed is *too* basic. According to Glennan’s definition, a mechanism is a complex system with causal components that interact via causal laws, i.e., it involves part-whole relations:

> A mechanism underlying a behavior is a complex system which produces that behavior by […] the interaction of a number of parts according to direct causal laws. (Glennan, 1996, 52).

Salmon’s and Glennan’s definitions are restricted to mechanisms in physics. Both definitions fall short of a *general* concept of causality. Causation *in general* cannot be reduced to mechanistic causations, as the case of causation by omission shows (according to Dowe, 2008). Glennan takes the opposite route: he attempts to reduce mechanistic explanations to causal laws. His goal is to explain higher-level causal processes in terms of lower-level laws, whereas the fundamental laws of physics that explain the higher-level processes according to him are not subject to mechanistic explanation. However, Glennan’s attempt to reduce mechanistic explanations to causal laws does also not work, insofar as it neglects the crucial part-whole relations supported by the causal laws.

In physics, the causal processes underlying a mechanism are often described in terms of a physical dynamics. The solar system, as the paradigm case of a mechanism of physics, is a complex bound system of bodies, with gravitation as the binding force that keeps the planets and moons in their orbits around the sun or the planets. In quantum mechanics, this example of a classical bound system of mechanical bodies has been generalized as follows. The atoms are described as bound systems of charged particles, i.e., an atomic nucleus plus N electrons described by an N-particle quantum mechanical wave function. The electrons within an atom have no orbits, but they are kept in bound quantum states via the Coulomb force; the underlying causal law is the N-particle Schrödinger equation. Analogously, the atomic nucleus is an N-particle system of protons and neutrons which are kept together according to the quantum laws of the strong interaction.

In biology, this approach is possible to the extent that chemical or biochemical mechanisms are at work, which in turn reduce to the mechanisms of molecular physics, in biophysics and genetics (cf. Odenbaugh & Griffiths, 2022). An example of applying the laws of physics to biophysical processes in a mechanistic explanation is the computer simulation of protein folding, which however is still a very complex problem without solution (Vallejos & Vecchi, Chap. 6, this volume). In cell biology, epigenetics, evolution theory, neurobiology, etc., the situation is also very complex and difficult. In many cases, the causal laws available to explain the way in which the causal components of a mechanism work are laws in a very weak sense. Or no causal laws at all are known, as in the case of the heuristic assumption of mental mechanisms (Bechtel, 2008). Therefore, philosophers of biology and neuroscience typically define a mechanism without recourse to causal laws:

> Mechanisms are entities and activities organized such that they are productive of regular changes from start or set-up to finish or termination conditions. […] Activities are the causal components in mechanisms. Mechanisms are composed of both entities (with their properties) and activities. Activities are the producers of change. Entities are the things that engage in activities. Activities usually require that entities have specific types of properties. (Machamer et al., 2000, 3.)

> Activities are the causal components in mechanisms. […] mechanisms are entities and activities organized such that they exhibit the explanandum phenomenon. (Craver, 2007, 6).

> A mechanism is a structure performing a function in virtue of its component parts, component operations, and their organization. The orchestrated functioning of the mechanism is responsible for one or more phenomena. (Bechtel & Abrahamsen, 2005, 423).

These definitions strikingly resemble the above dictionary definitions quoted above (Collins, 2012). According to them, mechanisms explain higher-level phenomena in terms of lower-level causal components, in a "dualistic" account of the components and their causal activities (Schiemann, 2019). Such explanations do not specify which kinds of causal activities are at work and how they relate to the causal entities. They just rely on the analogy between a complex system in nature and a machine with well-defined moving parts.

10.3.2 Causal Components and Their Dynamic Properties

Much philosophical confusion about the legitimacy of generalized mechanistic explanations arose from taking the mechanical analogy with the moving parts of machines too literally. To clarify the limits of this analogy a look at physics is helpful. For the case of physics, it is easy to specify the causal entities and their activities in precise terms, i.e., in terms of a physical dynamics. On this basis it is also easy to see how the concept of a mechanism can be generalized accounting for the physics after Newton, from electrodynamics to quantum mechanics and quantum field theory.

In contrast to the machinery of the gears inside a clock, the spatial structure of the parts of a mechanism is not necessarily decisive for the way it works, as the case of physics shows. Already William S. Malisoff (1940) made this point in defense of generalized mechanistic explanations. Indeed, the views about the mechanisms of nature in classical physics rely on reinterpreting the moving parts of mechanical machines in terms of idealized mathematical entities, such as the point masses and forces of mathematical physics:

> What did the physicists of 70 years ago speculate about? I should say they speculated about mechanism itself. What is a mechanism? […] A mechanism, they thought, is essentially a machine. And what is a machine? Simply enough, […] a thing of cogs and levers. (Malisoff, 1940, 405)

> The difference, however, between a physicist and a machinist was that the physicist's cogs and levers and machines consisted of mathematical points, lines surfaces, volumes, interacting by a system of forces between the points to which were attributed masses and velocities. (ibid., 405–406)

This observation perfectly agrees with Newton's account of the analytic-synthetic method of early modern science. Above all, it holds for the mechanism of the solar system. Classical mechanics replaces the celestial bodies by point masses, given that their extension is negligible as compared to the distance between them. It describes the causal properties of physical systems in terms of dynamic magnitudes such as mass or charge. For Malisoff, it is therefore obvious how to generalize the traditional mechanical physics to an up-to-date version of mechanistic explanations, in the age of relativity and quantum theory:

> Do we not still use forces, particles, and the like, where we can? (ibid., 414).

Leaving aside the role of idealizations in physics, another argument results in the same conclusion. A mechanistic explanation explains the functioning of a mechanism, or a machine, in terms of its causal components. A purely spatial interpretation of the part-whole relationship of a mechanism does not match the way the moving parts of a machine function. The relevant part-whole relation primarily concerns the causal properties, not the spatio-temporal properties of the components of a machine or a mechanism. It is a relation between the causal or dynamic properties of the whole on the one hand and its parts on the other. The parts of a mechanism act as dynamic parts. Their causal activities correspond to their dynamic properties.

Philosophers may object that the expressions "causal parts" and "dynamic properties" are unclear and much debated. Current philosophy spells dynamic properties out in terms of dispositions, and the concepts of causality range from various successors of Hume's regularity theory over variants of Salmon's physics-based approach to Woodward's interventionist account. But this should not worry us here. To cope with the mechanistic explanations in the practice of physics, the philosophical debates on dispositions and causality may be left aside. Instead, the above-mentioned physics-based approaches to causal laws and processes (Salmon, 1984, 1997; Glennan, 1996) matter, and, in addition, the part-whole relations that are constitutive for the dynamics of the compound systems described by physics.

A difficulty of relying on the causal laws and processes of physics is that different physical laws and theories give rise to several accounts of causality, from Einstein causality, i.e., the deterministic transmission of a physical signal within the light cone, to the irreversible processes that cause an entropy increase, or the indeterministic effects of a quantum measurement. Up to now, there is no unambiguous, well-established concept of causality or theory of causal processes that the physics community would share. There is no unified theory of physics, and the diverse concepts of causality used in the context of different theories cannot be unified either. But this should also not worry us here. To understand the mechanistic explanations of physics, we do not need a unified theory of physics but only models of specific physical phenomena with a well-defined underlying dynamic.

Beyond classical mechanics, *any* physical dynamics may give rise to mechanistic explanations in a generalized sense, from electrodynamics to thermodynamics, quantum mechanics, quantum field theory, or general relativity. Salmon (1984, 241) emphasized that mechanistic explanations in a generalized sense may even employ fields. The above case of the quantum mechanical description of atoms also shows that in general the parts of a mechanism do not need to be local, spatially well-identified parts. Any physical dynamics expresses the causal part-whole structure of a mechanism in terms of the dynamic properties of the whole and its constituent parts.

10.3.3 The "Atomistic" Constitution of Matter

From Newton's mechanics to quantum physics, the dynamic properties of physical systems and their components are conserved physical quantities such as mass, charge, energy, and so on. Particles in a generalized sense are collections of such dynamic properties for which conservation laws hold. The quantum revolution dispensed with particle trajectories. What remained, however, is the concept of particles as collections of conserved quantities such as mass, charge, etc., which cause the hits and tracks in particle detectors (Falkenburg, 2007). This generalized particle concept corresponds to Eugene P. Wigner's definition, according to which particles (or fields) are the irreducible representations of symmetry groups (Wigner, 1939). According to this most general particle concept, the relation between particles and forces, or interactions, rests on the dynamic symmetries associated with conservation laws for mass-energy, charge, spin, parity, and so on.

In particle physics, these conservation laws and their experimental tests in high energy scattering experiments have been decisive for the quark-parton constituent model of protons and neutrons. They paved the way towards the standard model of particle physics. The dynamics of a compound quantum system gives rise to sum rules for the conserved quantities of subatomic particles and the complex quantum systems made up of them. The quantum parts of matter are defined in terms of sum rules for mass-energy, momentum, charge, spin, parity, etc., which are empirically tested in the scattering experiments of atomic, nuclear, and particle physics (Falkenburg, 2007, chapters 4 and 6). In nuclear physics, the binding energy of the protons and neutrons adds to the sum of the masses of protons and neutrons. In the quark model of particle physics, the situation is similar, but more complex, given that here also gluons and quark-antiquark pairs contribute to the energy of the matter constituents measured in the scattering experiments of high energy physics. Similar sum rules, however, hold for the number and kinds of the quasi-particles in a solid, which are investigated in condensed matter physics (Falkenburg, 2015); or for the strength of an electromagnetic field and the occupation number of the corresponding quantum field, that is, for the intensity of light and the expectation value of the number of photons in this quantum field. In all these examples, the quantum parts of matter and light are subject to a dynamic part-whole relation, instead of being spatial parts of matter or fields.

So, the causal components of mechanistic explanations in current physics are dynamic parts of matter or fields, that is, the dynamic parts of the N-particle quantum systems that constitute matter or the N-particle quantum states that make up fields. These dynamic parts of matter or fields are particles in a generalized sense. The corresponding part-whole relations are sum rules for conserved quantities such as mass-energy, charge, spin, parity, and so on. The resulting mechanistic explanations are atomistic in a general sense, i.e., they rely on the generalized particle concept of the current quantum theories and particle physics. The "atoms" of current physics are the subatomic particles that exist according to the standard model of particle physics. This observation supports the following definition of a mechanism in physics:

> A mechanism is a complex system which produces a certain physical phenomenon by the interaction of a number of causal components with conserved dynamic properties that interact according to the laws of a physical dynamics and constitute the system as a whole in accordance with sum rules for the conserved quantities of this dynamics.

Here, the definitions suggested by Glennan (1996) and his followers are specified in terms of a physical dynamics, and Salmon's (1997) account is generalized in such a way that it includes the compound systems of physics. This approach substantially differs from that of dynamical system theory (cf. Kaplan, 2018) by including not only the differential equations of a physical dynamics, but also the related conserved dynamic quantities, which in turn are the basis for establishing a dynamic part-whole relation between a complex system and its causal components.

It should be added that mechanisms in this sense do not only explain processes, i.e., phenomena of change. They can also explain under which conditions there is *no* change. The mechanisms of classical mechanics or quantum mechanics explain the *stability* of compound systems of bodies or subatomic particles. Newton's theory of gravitation explains the stability of the solar system in terms of the approximate Kepler orbits of the planets and moons. Quantum mechanics explains why and under which dynamic conditions atoms and atomic nuclei are stable.

Nevertheless, the mechanistic explanations of physics in this sense have crucial limits. They cannot cope with mechanisms based on classical continuum mechanics or thermodynamics (for examples, see Falkenburg, 2019, 85–87). A quantum field with well-defined phase, but unsharp occupation number is obviously beyond the scope of the above definition. To what extent mechanisms in this sense can explain collective behavior such as phase transitions is also unclear. Philip W. Anderson is famous for his essay *More is Different* which emphasises that complex systems have many non-reducible properties (Anderson, 1972). In his introductory textbook on solid-state physics, which explains, e.g., how quantum physics explains the magnetic properties of solids, he emphasizes at the beginning: *"We do not know why there are solids"* (Anderson, 1997, 3).

Even if there is no *complete* (quantum) explanation of why (classical) solids exist, however, many properties of solids can be explained by the dynamics of their subatomic constituents. Therefore, ontological reduction works in physics *top-down* from macroscopic bodies to molecules, atoms, electrons, atomic nuclei, protons, neutrons, and finally, quarks and gluons; and mechanistic explanations in the above generalized sense suggested here work *bottom-up* for the constitution of matter in terms of the dynamic properties of subatomic particles.

10.4 Mechanistic Explanations in Neuroscience, and Their Limits

So, what are generalized mechanistic explanations good for? The above-mentioned restrictions suggest that the definition suggested in Sect. 10.3.3 only works if the *number* of causal components of a mechanism is well-defined. Otherwise, to talk of a mechanism seems to be a mere *façon de parler*, since any analogy with the functioning of a machine fails. Two other obvious necessary conditions for a successful mechanistic explanation in the sense of Sect. 10.3.3 are that the *dynamic properties* of the causal components are known, and that it is possible to specify a *dynamic part-whole relation* that connects the properties of the complex system with the properties of its causal components. In physics, this part-whole relation is defined in terms of the sum rules that hold for mass-energy, momentum, charge, spin, parity, etc. To a large degree, this approach can also be generalized to the higher-level explanations of chemistry, biochemistry, molecular biology, and neurobiology. Many of these mechanisms work via electro-chemical signal transmission, for which the conservation laws of charge and energy hold. Hence, their basis is a physical dynamics, as in the electric circuit model of signal conduction along the membrane of an axon (Hodgkin & Huxley, 1952) which is based on the laws of electrodynamics.

These considerations also shed light on the scope of mechanistic explanations in neuroscience. The theory of neural mechanisms is based on the Hodgkin-Huxley model just mentioned, the laws of chemical signal transmission through the synapses, and the theory of artificial neural networks. The theory of artificial neural networks describes the functioning of the parallel computers which underly the technological achievements of machine learning etc., which have gained increasing importance in all scientific disciplines and branches of technology during the last decades. Here, the analogy between processes in nature and the way a machine works runs in both directions: Artificial neural networks are modelled after the structure and functioning of neural networks; and, vice versa, the way the neural network in the brain functions is interpreted in terms of the functioning of a parallel computer. So far, so good. A parallel computer is a complex system, the causal components of its hardware function according to the laws of physics, and in this respect, it is a mechanism in the sense of Sect. 10.3.3. The phenomenon which this mechanism produces is the computer output of a calculation, and/or the way in which a robot moves according to the results of the calculation.

To compare the neural network in the brain with a computer is an important heuristic tool of computer science as well as neuroscience. The computer model of the brain is a highly idealized, strongly simplified, very crude model of the brain, given that the brain is the most complex system known in the universe. But planets, too, are no mass points; nor belong the atoms and their constituent parts to the laws of classical mechanics; and the computer model of the brain is no more wrong or less true than Newton's atomic model was. Even though the laws of classical mechanics failed in atomic physics, the classical atomic model of Rutherford, and its deficiencies, paved the way first to Bohr's atomic model, and then, to quantum mechanics.

However, the analogy between the brain and a computer crucially differs from Rutherford's analogy between the atom and the solar system, or from Newton's way of attributing the dynamic properties of mechanical bodies to the atoms, following his third, inductive, rule of philosophizing (Sect. 10.2.2). The celestial bodies in the solar system, the atoms, and the subatomic constituent parts of matter share the dynamic property of mass. The law of gravitation, the Coulomb law of electrodynamics, and the Schrödinger equation of the hydrogen atom predict compound N-body or N-particle systems which are bound together by the conserved dynamic properties of (gravitational) mass and electric charge. But no mechanism is known that might explain how the brain produces the conscious human mind. No dynamics is available for the relation between brain and mind, nor do the brain and the mind share any properties on which the analogy between the brain and a parallel computer may rely. To bring then "information" into play is more confusing than illuminating. The mathematical information processed by a computer is obviously *not* the kind of information which we understand with our conscious mind. Mental phenomena and our cognitive capacities, here, and the neural mechanisms in the brain, there, do not share any obvious dynamic properties, for which a kind of a part-whole relation may be established.

Brain and mind, or our neurons and our ideas, do not stand in any known kind part-whole relation. Both are localized in our heads, but no spatial, dynamic, or causal relations between them are known, it is only possible to find and investigate specific correlations between them. So, cognitive neuroscience investigates the correlations between the neural activities in certain brain areas, on the one hand, and the contents of a test person's consciousness or certain cognitive capacities of a human being or an animal, on the other, and this is not in vain. In his book *Mental Mechanisms*, William Bechtel correspondingly emphasizes that cognitive neuroscience may employ heuristic identity assumptions about mental phenomena and their physical basis in neural mechanisms:

> One of the virtues of viewing identity as a heuristic claim is that it can guide not only the elaboration of the two perspectives which are linked by the identity claim, but it can use each to revise the other. (Bechtel, 2008, 71).

This heuristic identity claim gives rise to the term "mental mechanism". The respective heuristics is most fruitful for cognitive neuroscience, but to talk of "mental mechanisms" is here not associated with any mechanistic explanation proper discussed in this paper or in the recent debate.

10.5 Some Important Caveats

Yet it remains unclear how far we may go in generalizing genuine mechanistic explanations that indeed *explain* their explanandum from the causal components of a complex system. Moreover, I must confess that in the end it also remains unclear what a *genuine* mechanistic explanation is. In Sect. 10.3.3 I proposed to generalize mechanistic explanations in terms of the physical dynamics of a complex system and the conserved quantities of its causal components. However, to what extent can this explanation be generalized to higher-level mechanisms *beyond* physics? There are at least two more crucial caveats. Both are closely related to the limits of theoretical reduction.

First, in chemistry, biochemistry, and molecular biology, structural considerations become quite important for understanding mechanisms, and with them again the spatial structure of the causal components, which a physical dynamics neglects. In this sense, for higher level mechanisms the old concept of a mechanism as a machine is not completely off the mark, and so it is not completely metaphorical to speak of chemical, biochemical, or biological machines.

Second, neglecting the environment of a mechanism often leads to inadequate idealizations. This point becomes already evident in physics if we look at the decoherence approach to the quantum measurement problem (Bacciagaluppi, 2020). To speak of the mechanism of decoherence is to explain quantum measurements in (probabilistic) terms of the interaction between an entangled quantum system-plus-measurement device and its environment. Understanding mechanisms often means looking not only top-down at the causal parts of a mechanism and their interactions, but also bottom-up at the way the mechanism is embedded or situated in its environment, as examples from higher-level sciences show, too (Bechtel, 2009; Bechtel & Abrahamsen, 2009).

10.6 Summary and Conclusions

The concept of a mechanism and the corresponding account of mechanistic explanations draw on the old analogy between machines and processes in nature. In view of scientific and technological progress, it is justified to generalize them from the traditional mechanistic explanations based on classical mechanics to current scientific practice. These generalizations have their counterpart in a generalized mechanistic methodology, which is typical of the "dissecting" sciences (Schurz, 2014, 35). This methodology, which aims first at decomposing natural phenomena *top-down* into lower-level causal components, and then, at giving *bottom-up* mechanistic explanations, traces back to the analytic-synthetic methods of early modern science, with Newton's methodology as one of its most important roots. The method of dissecting the phenomena to explain them in mechanical terms became most successful in eighteenth and nineteenth century science. In twentieth century physics, however, the quantum revolution dispensed with the restriction of scientific explanations to classical mechanisms. Quantum mechanics provided new, generalized, mechanistic explanations, with quantum particles and field quanta as the causal components of mechanisms that explain the constitution of matter in terms of dynamic part-whole relations. These part-whole relations connect the properties of complex systems with the conserved dynamic quantities of subatomic particles. These conserved quantities satisfy well-defined conservation laws and support the definition of a mechanism in terms of sum rules that hold for conserved quantities. This definition generalizes Salmon's account of mechanistic explanation to compound systems, and it specifies the definitions given by the proponents of the "new mechanisms" in terms of a physical dynamics.

This definition of a mechanism in a generalized sense is in accordance with the practice of atomic, nuclear, and particle physics, and it explains why and to what extent ontological reduction in physics is justified. But quantum fields with unsharp occupation number, continuous systems, and collective behavior such as phase transitions are beyond its scope, and it remains unclear whether it is more than a mere *façon de parler* to talk of the *mechanisms* underlying such phenomena. For the higher-level mechanisms of chemistry, biochemistry, and biology, further crucial limits of the approach must be considered, given the limits of theoretical reduction.

Another limit of mechanistic explanations not only for the approach suggested here, but also in a more general sense concerns the mental phenomena investigated by cognitive neuroscience. To talk of neural mechanisms indeed fits in with the definition in terms of a physical dynamics. The underlying models are based on the laws of electrodynamics and electro-chemistry, and they are associated with the conserved quantities of charge and energy. To extend this talk to the relation between brain and mind, however, seems to be beyond the scope of any mechanistic explanation, as far as such an explanation seems to require that the *phenomenon explanandum* of a complex system and its causal components share at least *some* dynamic property.

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Literature

Achinstein, P. (1991). *Particles and Waves. Historical Essays in the Philosophy of Science*. Oxford: Oxford University Press.

Anderson, P. W. (1972). More is different. *Science, New Series, 177*, 393–396.

Anderson, P. W. (1997). *Concepts in solids*. World Scientific.

Bacciagaluppi, G. (2020). The role of decoherence in quantum mechanics. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Fall 2020 ed.) https://plato.stanford.edu/archives/fall2020/entries/qm-decoherence/

Beaney, M. (2021). Analysis. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Summer 2021 ed.) https://plato.stanford.edu/archives/sum2021/entries/analysis/

Bechtel, W. (2008). *Mental mechanisms: Philosophical perspectives on cognitive neuroscience*. Psychology Press.

Bechtel, W. (2009). Looking down, around, and up: Mechanistic explanation in psychology. *Philosophical Psychology, 22*, 543–564.

Bechtel, W., & Abrahamsen, A. (2005). Explanation: A mechanist alternative. *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences, 36*, 421–441.

Bechtel, W., & Abrahamsen, A. (2009). Decomposing, recomposing, and situating circadian mechanisms: Three tasks in developing mechanistic explanations. In H. Leitgeb & A. Hieke (Eds.), *Reduction and elimination in philosophy of mind and philosophy of neuroscience* (pp. 178–190). Ontos.

Collins, W. (2012). mechanism. In *Collins English dictionary - complete & unabridged* (10th ed.). HarperCollins Publishers. http://www.dictionary.com/browse/mechanism. Accessed 14 May 2017.

Cotes, R. (1713). Editor's Preface to the Second Edition. In: Newton 1726, 385–399.

Craver, C. F. (2007). *Explaining the brain. Mechanisms and the mosaic unity of neuroscience*. Clarendon Press.

Crombie, A. C. (1953). *Robert Grosseteste and the origins of experimental science 1100–1700*. Clarendon Press.

Churchland, P. M. (1995). *The engine of reason, the seat of the soul*. MIT Press.

Dowe, P. (2008). Causal processes. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Fall 2008 ed.) http://plato.stanford.edu/archives/fall2008/entries/causation-process/

Engfer, H. J. (1982). *Philosophie als analysis*. Fromann-Holzboog.

Falkenburg, B. (2007). *Particle metaphysics. A critical account of subatomic reality*. Springer.

Falkenburg, B. (2012). *Mythos Determinismus. Wieviel erklärt uns die Hirnforschung?* Springer.

Falkenburg, B. (2015). How do quasi-particles exist? In B. Falkenburg & M. Morrison (Eds.), *Why more is different. Philosophical issues in condensed matter physics and complex systems* (pp. 227–250). Springer.
Falkenburg, B. (2019). Mechanistic explanations generalized: How far can we go? In B. Falkenburg & G. Schiemann (Eds.), *Mechanistic explanations in physics and beyond* (pp. 65–90). Springer Nature Switzerland.
Geyer, C. (Ed.). (2004). *Hirnforschung und Willensfreiheit*. Suhrkamp.
Glennan, S. (1996). Mechanisms and the nature of causation. *Erkenntnis, 44*, 49–71.
Hintikka, J., & Remes, U. (1974). *The method of analysis: Its geometrical origin and its general significance* (Boston studies XXV). Reidel.
Hobbes, T. (1655). *De corpore*. In J. C. Gaskin (Ed.), *Thomas Hobbes: The elements of law, natural and politic; Ch. IV* (pp. 193–212). Oxford University Press. 1999.
Hodgkin, A. L., & Huxley, A. F. (1952). A quantitative description of membrane current and its application to conduction and excitation in nerve. *The Journal of Physiology, 117*, 500–544.
Kaplan, D. M. (2018). Mechanisms and dynamical systems. In S. Glennan & P. Illaris (Eds.), *The Routledge handbook of mechanisms and mechanical philosophy* (pp. 267–280). Routkledge.
Lindberg, D. C. (1971). Lines of influence in thirteenth-century optics: Bacon, Witelo, and Pecham. *Speculum, 46*, 66–83.
Lindberg, D. C. (1976). *Theories of vision from al-Kindi to Kepler*. University of Chicago Press.
Losee, J. (1993). *A historical introduction to the philosophy of science* (3rd ed.). Oxford University Press.
Lucretius. (1570). *De rerum natura*, ed. by D. Lambin, Paris.
Machamer, P., Darden, L., & Craver, C. F. (2000). Thinking about mechanisms. *Philosophy of Science, 67*, 1–25.
Malisoff, W. M. (1940). Physics: The decline of mechanism. *Philosophy of Science, 7*(1940), 400–414.
Newton, I. (1726). *The principia. Mathematical principles of natural philosophy*. A new translation by I. Bernhard Cohen and Anne Whitman. Univ. of California Press. 1999.
Newton, I. (1729). *Principia. Sir Isaac Newton's mathematical principles of natural philosophy and his system of the world. Vol. I: The motion of bodies. Vol. II: The system of the world*. Mott's translation revised by Cajori. Univ. of California Press 1934, 1962.
Newton, I. (1730). *Opticks or treatise of the reflections, refractions, inflections & colours of light*. Based on the fourth edition: London 1730. Dover 1952, 1979.
Odenbaugh, J., & Griffiths, P. (2022). Philosophy of biology. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Summer 2022 ed.) https://plato.stanford.edu/archives/sum2022/entries/biology-philosophy/
Pappus of Alexandria. (1589). Pappi Alexandrini *Mathematicae Collectiones*. English edition: Pappus of Alexandria, *Book 7 of the Collection*. Part 1. Edited with Translation and Commentary by Alexander Jones. New York 1986. – Quoted after the translation in Hintikka & Remes 1974.
Salmon, W. (1984). *Scientific explanation and the causal structure of the world*. Princeton University Press.
Salmon, W. (1997). Causality and explanation: A reply to two critiques. *Philosophy of Science, 64*, 461–477.
Schiemann, G. (2019). Old and new mechanistic ontologies. In B. Falkenburg & G. Schiemann (Eds.), *Mechanistic explanations in physics and beyond* (pp. 33–46). Springer Nature Switzerland.
Schurz, G. (2014). *Philosophy of science: A unified approach*. Routledge.
Singer, W. (2003). *Ein neues Menschenbild? Gespräche über Hirnforschung*. Suhrkamp.
Singer, W. (2004). *Verschaltungen legen uns fest. Wir sollten aufhören von Freiheit zu sprechen*. In Geyer 2004, 30–65.
Roth, G. (2003). *Fühlen, Denken, Handeln: Wie das Gehirn unser Verhalten steuert*. Suhrkamp.
Rubia, F. L. (2009). *El fantasma de la libertad. Datos de la revolución neurocientífica*. Editorial Crítica.

Unguru, S. (1974). Pappus in the thirteenth century in the Latin west. *Archive for History of Exact Science, 13*, 307–324.
Vesalius, A. (1543). *De humani corporis fabrica libri septem*. Johannes Oporinus.
Wigner, E. P. (1939). On Unitary Representations of the Inhomogeneous Lorentz Group. *Annals of Mathematics, 40*, 149–204.
Worrall, J. (2000). The scope, limits, and distinctiveness of the method of 'deduction from the phenomena': some lessons from Newton's 'demonstrations' in optics. *Brit J Phil Sci, 51*, 45–80.