Winfried Thielmann

Concept Formation in Physics from a Linguist's Perspective

Abstract: This chapter explores concept formation in physics from a linguist's point of view. After some preliminary reflections on conceptual structures, the chapter attempts to demonstrate that the key concept of modern physics is the body concept as introduced by Galileo. In stark contrast to the concepts we usually possess, the body concept is an operational concept, i.e. a concept the purpose of which is the levelling of ontological differences. Employing operational concepts in the natural sciences shifts the line of inquiry from how natural things are to how we can manipulate them. The answers we get to such questions are – even though they involve nature – not about nature, but about our interaction with nature. If we continue forgetting about the role of human agents in scientific inquiry, physics may, however, prevail at the very bottom of the epistemological well at which Eugene Wigner marvelled at the “the miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics”.

1 Introduction

There is a certain halo about the terminology of physics. Expressions such as *quantum leap*, *half-life*, and *synergy* have even made it into ordinary language – after having exhausted their use-by date as exclusivity markers of CEO-jargon, where they used to play a role similar to that of an expensive *eau de toilette*. This chapter, however, is not about terminology, but about concepts. My intention is to conduct an enquiry into the *conceptual* steps that brought about the physics of the modern era. I shall argue that physics is still, on the whole, quite ignorant of these steps – not least, because the terms naming the concepts involved are very ordinary: *body*, for instance, or *velocity*, and *force*.

After some preliminary linguistic remarks about concepts in general, I shall explore, in several steps, the conceptual transformations inherent in Galileian and Newtonian physics that, to this day, largely determine how physicists conceive of the world and their own scientific enterprise.

2 Concepts

In everyday discourse we frequently do not bother too much about distinguishing between *word*, *name*, *term*, *notion*, *idea* or *concept*. The point I am attempting to make in this section is that there is a crucial difference between the words we utter and the ideas that are named by some of the words we utter.

Let us imagine two people taking a morning walk in the forest. They are having friends over for dinner and are talking about whether or not to bring up a second table to have enough room. Walking between trees they are able, without any effort, to discuss things not present – tables for instance. This example involves a function of language not too frequently recognized even by linguists, the *gnoseological function* (Ehlich 2007): language, as the prime human medium for knowledge retention and transfer, allows for transindividual representation of reality by making knowledge communicable. This is, of course, the very function of language that acts as a prerequisite for phenomena such as texts and, of course, literature.

The following model (Ehlich and Rehbein 1986) displays the instances of reality involved in this example. We have a speaker S, a hearer H – both represented by their mental spheres Π_S and Π_H – the section of extralinguistic reality where speaker and hearer are present, i.e. the forest, represented by P, and the speaker's utterance about an additional table to be brought up, represented by p (Fig. 1):

Fig. 1: Instances of reality involved in a speech situation (Ehlich and Rehbein 1986, 96).

In the case discussed here, where people speak about something not present, the current extralinguistic reality (P) of the speaker and hearer, i.e. the forest, is not relevant (Fig. 2):

Fig. 2: Linguistic representation of things absent (modification of Ehlich and Rehbein 1986, 96).

What is required for communication about things not present? The main thing is that both speaker and hearer have a common knowledge base regarding the subject discussed, in our case tables. They do so because they are part of a societal practice that involves such artifacts.

What claims can be made about this common knowledge base? Without delving into a debate about mental representations, impressions or ideas, we can safely state that this knowledge is of a kind that allows for *linguistic* representation. Aristotle suggested a well-known method for putting this kind of knowledge into language, involving the two steps *genus proximum* and *differentia specifica*, for instance: *A table is a piece of furniture with legs and a smooth flat top*. Children have a different way of phrasing such types of knowledge: *Table is what you sit at*. A table is, and I believe we can all agree to this, made by humans to fulfil certain purposes (*sit at*) and shaped according to these purposes (*smooth flat top*). The semanticist Anna Wierzbicka has shown that natural objects – as well as people – are conceived of in a very similar fashion (1985), i.e. similar to artifacts. I call such conceptual structures *thing concepts*. Thing concepts are the most important and fundamental concepts we have: they are our link to reality, as societal beings. I have suggested that these conceptual structures – not the things or concepts themselves, but their intrinsic makeup – are universal (Thielmann 2009). Abstract concepts can always be traced back to thing concepts. *Love* is something occurring between people. So is a *contract*, as a system of action paths opened for or closed to parties ultimately consisting of people, with consequences attached to each action path.¹

As we have seen, we are, from linguistic interaction, used to handling linguistic expressions that either name thing concepts (*table*) or that can be traced back to such knowledge structures (*love*, *contract*). Why have I spent so much time discussing these things when, after all, this is supposed to be a paper about concept formation in physics? This is because the conceptual side of the physics of the modern era is nothing other than a huge attack on and a transgression of thing concepts. Overcoming thing concepts is, I shall argue, the main achievement of modern physics, its main characteristic and, ultimately, the reason for the discipline's loss of reality.

¹ Metaphors (for example Lakoff and Johnson 1980) play a crucial role in addressing new, previously uncharted, areas (e.g. *potential well*), allowing us to conceive of new things by applying the thing concepts we already possess.

3 Newton's second law of motion

I shall start my argument with the following well-known formula, Newton's Second Law of Motion:

$$F = ma$$

Force is the product of mass and acceleration. The formula states a relationship between force, mass, and acceleration, i.e. the change in velocity over time:

$$F = m \frac{dv}{dt}$$

The things expressed by this formula appear to be quite close to common sense: If something is subjected to a force, its velocity changes, i.e. it speeds up or it slows down. The larger the mass of the object, the stronger the force necessary to achieve the same change in velocity. However, what is the something here that is subjected to a force? A car? A bullet? A planet? And if this formula does indeed not distinguish between cars, bullets or planets, would this not imply that the differences between different things are of no importance here? Obviously, the nexus mathematically expressed by this formula concerns something that does not occur within this formula. Even though we are dealing with physics at school level here, it appears that we are confronted with conceptual structures fundamentally different from those we encounter in ordinary life. For the nexus we are looking at concerns something quite devoid of conceptual specification.

These issues regarding Newton's Second Law of Motion are by no means trivial. The formula expresses a nexus, but the very thing the nexus is about does not show up in the equation. The reason for this lies in the approach to reality that characterizes modern physics. The conceptual step that brought this physics about is the hour of birth of modern physics – and of a concept of which physics has remained largely ignorant.

4 Free fall

To understand what the physics of the modern era is about we have to cast a closer look at its founder: Galileo. As for natural philosophy, Galileo's contemporaries were still, by and large, deeply imbued by Scholasticism, i.e. a scholastic interpretation of Aristotle's physics. To them, it was perfectly natural to put their questions to canonic texts, rather than to nature. Hence, natural

philosophers of Scholasticism did not direct their questions at reality, but at Aristotle's texts about reality. Galileo's interest is different, as the beginning of the *Discorsi* illustrates:

Sagredo. [...] Nevertheless, what we were told a little while ago by that venerable workman is something commonly said and believed, despite which I hold it to be completely idle, as are many other things that come from the lips of persons of little learning, put forth, I believe, just to show they can say something concerning that which they don't understand.

Salviati. You mean, perhaps, that last remark that he offered when we were trying to comprehend the reason why they make the sustaining apparatus, supports, blocks, and other strengthening devices so much larger around that huge galley that is about to be launched than around smaller vessels. He replied that this is done in order to avoid the peril of its splitting under the weight of its own vast bulk, a trouble to which smaller boats are not subject.

(Galilei 1974, 11–12)

The time at which Galileo conceives of his new physics is characterized by a – diversifying – societal practice of maxim-driven production devoid of a conceptual basis. This is why Galileo does not question nature; he questions the opportunities for societal production availing itself of nature. Consequently he does not try to describe natural objects in the way they present themselves to us without our interference (this would have been Aristotle's approach). He is interested in the regularities according to which natural objects can be *manipulated*.² At this point, however, an important conceptual step occurs: While Aristotelian physics and the natural philosophy of Scholasticism had not only accepted that natural objects are individuals, i.e. different from one another, but in fact made this the very basis of their arguments, Galileo treats all objects the same regardless of their differences in nature. In fact, he even ceases to distinguish between natural objects and human artefacts. This important conceptual step is not obtained through experiments, but through reasoning.

Aristotle taught that all natural objects fall at their own speed determined by nature. A big, heavy rock, for instance, falls faster than a small one. Galileo reasons (1974, 66–67 and 1965, 106–107) that if this were true and one tied the smaller rock to the bigger one, the smaller one – falling less quickly – would have to slow down the bigger one. Since the composite, however, would have to move at even greater speed, being heavier than each of the single rocks, one would arrive at the absurd conclusion that the composite would fall faster and slower at the same time. The solution can only be that everything falls at the same speed.

² Von Wright writes: “one can make a strong case for the thesis that causation in the natural sciences (better: causation in nature) is primarily and on the whole of the manipulative type” (1975, 110).

Aristotle would not have accepted this argument, since the composite, being a human artefact, differs essentially from the two natural objects, which is why – according to him – no claim could be made about it.

From this it should be clear that the question of whether or not all things fall at the same speed cannot be answered by experiment. The *Deutsches Museum* in Munich has on display an evacuated glass pipe containing a feather and a small lead ball. With both items at the bottom, you quickly turn the glass pipe upside-down and then observe that both things hit the bottom pretty much at the same time. But if you used a high quality release mechanism and detectors, you would always observe small time differences. In this case, a modern physicist would say that both release mechanism and detectors were of high quality, whilst an Aristotelian would find his view confirmed that there are ontological differences between things showing up even in an experiment of this kind. The question of whether or not all things fall at the same speed cannot be resolved, but it can be – plausibly – *decided*. This is, however, a step of *axiomatic* character, the axiom being that all things fall at the same speed.

The *decision* to accept that naturally occurring objects and artifacts, regardless of their ontological differences, fall at the same speed, leads to a new conceptual structure: the *body concept*. When viewed through the conceptual lens of the body concept, ontologically different natural things become ontologically the same: objects that differ only according to measurable dimensions (mass, volume etc.). The introduction of this concept has an important consequence: Since all objects move in the same fashion, one can *manipulate artifacts* in order to say something about nature.

The body concept is a conceptual structure of a new kind. It is an *operational concept*. Operational concepts are the key concepts of modern physics. By means of operational concepts an area of nature can be made available for quantitative exploration, which implies, at the same time, the abolishment of the structures of knowledge we have characterized above as thing concepts. With the introduction of operational concepts, physics sheds its previously hermeneutic orientation and becomes purely operational. There being no difference between natural objects and human artefacts, apparatuses can be invented to find out regularities of movement by investigating a body's path within suitably designed reference spaces of time and distance. These regularities built upon the operational concept of body and the concepts of uniform and accelerated movement are, however, not *laws of nature*, but conditions applying to a societal production availing itself of nature. The main characteristic of modern physics is the levelling and negation of the very conceptual structures we employ to make sense of our ordinary societal reality.

By the way: Galileo's radical conceptual step, without which there would be no modern physics, was by no means accompanied by terminological innovation. Galileo continued using the scholastic term *mobile*; the term *corpus* (*body*) was introduced later, by Descartes (Galilei 1974, xxxv).

Equipped with the body concept, Galileo was able to answer a question that occupied him for many years: What distances do bodies, after release, travel in equal times? Compared to the questions asked by hermeneutic Aristotelian natural philosophy, this question is purely operational. Galileo does not ask *why* something falls, but *how*.

The body concept has two facets: It determines an epistemological approach to nature and it creates the basis for the manipulation of artifacts in the place of nature. Since all bodies fall at the same speed, an *apt* body can be produced (e.g. a bronze ball) that *falls* as a representative of all bodies. From this there is a straight path to Newtonian Mechanics: Since all bodies fall at the same speed, one can look for a property that is common to all bodies and responsible for weight: *mass*. This makes it possible to conceive of accelerated motion, i.e. any change of motion, as something brought about by *force*.³ Thus, the concept of force, i.e. Newton's Second Law of Motion, is – in a way that is not altogether obvious – built upon the operational body concept. The concept of force is a second degree operational concept.

As I have attempted to demonstrate, modern experimental physics, as established by Galileo, does not investigate nature, but the regularities to which human interaction with nature is subject. To answer the question of how things – as bodies – fall, Galileo manufactures an apparatus that simulates nature. According to the reconstructions of Stillman Drake, time and space, too, are turned into manufactured conditions for the production of physical knowledge. To answer the question of what distances are travelled by bodies in equal times, Galileo had to devise a way to produce small time intervals, as he did not have precise clocks or strobes. As Stillman Drake writes, Galileo quite possibly used his – subjective – feeling of rhythm to judge small time intervals:

Galileo's procedure, as I reconstruct it, was this. He tied gut frets around his grooved plane, as frets are tied on the neck of a lute, so that they are snug but can be moved as needed; to set their initial positions it sufficed to sing a march tune, release the ball on one beat, and mark its approximate positions at following beats. With the frets roughly in place, the ball made a sound on striking the plane after passing over each one; they were

³ The equivalence of inert and heavy mass is a direct consequence of the body concept invested into Newtonian dynamics: Since all bodies fall at the same speed, i.e. experience the same acceleration, and weight, as a force, acts upon inert mass, weight has to be proportional to mass.

then adjusted until each of those sounds was judged to be exactly on a beat. It remained only to measure their distances from the point at which the resting ball touched the plane. (Drake 1978, 89)

It is quite telling that this experiment by which Galileo very likely found the regularities of the movement of falling bodies was not included in the *Discorsi* – quite possibly because scholastically inclined readers would have regarded the experimental procedure as inexact. In the *Discorsi*, time is measured by a water clock – a device that, at first, sounds more convincing than a march tune and rhythmical intuition, but does not work at all, as Alexandre Koyré and others have pointed out.⁴

The manufacturing of distances was, quite possibly, conducted according to the following procedure:

Take a short ruler divided accurately into sixty equal parts as small as you can conveniently see; mark a long rod at intervals equal to the length of your ruler, and you can quickly measure with great accuracy any distance not longer than the rod, to those units. (Drake 1978, 86–87)

Galileo's physics, in the rough sketch I have provided here,⁵ is an engineer's physics: Based on the operational body concept, this physics allows for the manipulation of artifacts as representatives of natural objects. However, the true object of investigation is not nature, but the regularities of human interaction with nature. Manufacturing reference spaces of time and distance, and producing apparatuses in which processes that are seen as representative of natural processes are instigated, man creates knowledge about his own – thus measured – possibilities of interaction with nature. Viewed from this perspective, Galileo's physics is a mathematically guided anthropology that opens up for man new areas of safe and reliable action and production.⁶

⁴ “A bronze ball rolling in a ‘smooth and polished’ wooden groove! A vessel of water with a small hole through which it runs out and which one collects in a small glass in order to weigh it afterwards and thus measure the times of descent (the Roman water-clock, that of Ctebius, had been already a much better instrument): what an accumulation of sources of error and inexactitude!” (Koyré 1953, 224).

⁵ For a comprehensive account see Thielmann 1999, 153–205.

⁶ Describing Galileo's physics as an engineer's physics may seem as an affront to theoretical physicists who – especially nowadays where even pure research is judged according to *impact* and applicability – might believe that I am intent on reducing the ancestor of modern physics to the *pits* of mechanical engineering. The only thing I wish to emphasize, however, is that Galileo not only possessed the theoretical mind of a genius – a department where, for instance, the great scholastic philosopher Jean Buridan would have measured up quite well – but also had a keen interest in physical reality and application, and the hands and craftsmanship to go with such a mind, and such an interest.

The importance of Galileo's redirection of the line of enquiry from *why* to *how* cannot be over-emphasized. The natural philosophers of scholasticism wanted to find out why things are the way they are. Their line of enquiry was hermeneutic. Replacing *why* with *how*, Galileo sacrifices conceptual insight for operational success.

By the argument laid out here, I by no means wish to suggest that the line of inquiry of modern physics or its insights are flawed. The point I mean to make is that by shifting the line of inquiry from how natural things are to how we can manipulate them, the answers we get to our questions are – even though they involve nature – not about nature, but about our interactions with nature. Our interaction with nature is modern physics' real object of investigation. If we forget about our own part in this game, we are likely to mistake the regularities to which our interactions with nature are subject for laws of nature. Such reification of *laws of nature* means, however, nothing other than losing sight of the reality truly subjected to inquiry. This is the epistemological somersault occurring in Newtonian mechanics.

5 The removal of agents

Within Galileo's physics, the reference spaces of time and distance are manufactured conditions; it is a physics where human agents are still visible. Newton, however, proceeds to take man out of the equation once and for all. For he declares that time and space are not manufactured conditions, but properties of nature itself:

Absolute, true and mathematical time, within itself and by its own nature without regard to anything external, flows equably, and by another name is called duration: [...] Absolute space, by its own nature without regard to anything external, remains always the same and immobile: [...].⁷ (Newton 1972, 46)

Why is this step so important? The fundamental question *utrum tempus habeat esse extra animam* – whether time exists outside the human mind – is one of the key questions of Scholasticism (Maier 1955). By stating that time and space are properties of nature, Newton by no means settles this debate, but makes a fundamental decision about the ontological status of space and time in modern

⁷ Transl. by WT. "Tempus absolutum, verum, & mathematicum, in se & natura sua sine relatione ad externum quodvis, æquabiliter fluit, alioque nomine dicitur duratio: [...] Spatium absolutum, natura sua sine relatione ad externum quodvis, semper manet simile & immobile: [...]" (Newton 1972, 46).

physics. What we observe here is a step quite similar to Galileo's *decision* that there is no ontological difference between natural objects and human artifacts. In other words: The beginning of modern physics consists in *decisions* about the ontological status of natural objects, space and time. By taking man – in Galileo's physics still the manufacturer of space and distance – out of the equation, Newton achieves a physics where the regularities of human interaction with nature acquire the status of natural laws.

The price paid for this is something from which modern physics, I believe, has never quite recovered: The loss of the true object of investigation, human interaction with nature, is responsible for the conceptual crises of the physics of the twentieth century and beyond, where there is a tendency to mistake purely operational concepts for ontological concepts, i.e. concepts of an explanatory nature. The question of whether light consists of waves or particles cannot be settled within physics, because *wave* and *particle* are not explanatory concepts. On the contrary, *wave* and *particle* are both second degree operational concepts that have been successfully employed in making certain aspects of the phenomenon of light available for quantitative exploration. Interference of light beams is dealt with by applying the operational concept of *wave*, whilst the regularities of photo-electric processes can be established by applying the operational concept of *particle*. Both concepts being operational concepts, their merit does not go beyond the success of the operational procedures they make possible. The question of *what light really is* could be rephrased as *what structures of reality allow us to employ the operational concepts of wave and particle successfully?* This question, being ontological, cannot be answered within physics.⁸

With Newton, physics lost its real object of investigation, i.e. the regularities of human interaction with nature. These regularities are, instead, being

⁸ Heisenberg (1930, 39) conducts a thought experiment that he interprets in a way that illustrates the fallacy of reifying operational concepts: A photon, represented by a wave packet, travels through a semi-transparent mirror. The mirror decomposes the wave packet in two parts. "If an experiment yields the result that the photon is, say, in the reflected part of the packet, then the probability of finding the photon in the other part of the packet immediately becomes zero. The experiment at the position of the reflected packet thus exerts a kind of action (reduction of the wave packet) at the distant point occupied by the transmitted packet, and one sees that this action is propagated with a velocity greater than that of light. However, it is also obvious that this kind of action can never be utilized for the transmission of signals so that it is not in conflict with the postulates of the theory of relativity." As Popper points out in his *Postscript* (1982, 100 and 115), Heisenberg treats the wave packet as a natural object rather than an operational concept, a reification by which he loses sight of wave packets being the description of a superimposition of an – ideally infinite – series of experiments conducted by observers.

mistaken for laws of nature itself. In the history of the discipline, these processes are accompanied by massive abstractions (e.g. Lagrange's *Analytical Mechanics*, 1788) and the operationalization of new areas: The concept of gas in thermodynamics or the concept of wave packet in quantum mechanics are operational concepts of the same structure as the body concept they rely on. It is only when confronting the microcosm that man can no longer take himself out of the equation, but has to factor himself into operational proceedings.

It is befitting that human action is ignored in the epistemological foundation of Newtonian physics: In Kant's *Critique of Pure Reason* [*Kritik der reinen Vernunft* (1990 [1781])] time, space and causality are part of human cognitive equipment – where phenomena are, by definition, spatial, temporal and causal, any question as to their real makeup is settled in advance. Philosophy of science of the twentieth century continues to see the purpose of physics as investigating the laws of nature (Janich 1978). Theorists such as Carnap (1926), Popper (1935) and Hempel (1952, 1966) place major emphasis on the logic of induction – i.e. that the findings of physics are only supported by a finite number of experiments. This is quite ironic, since experimental proceedings – designing and building of apparatuses, waiting for and measuring results etc. – presuppose a reliability of reality without which *ex post* epistemological reasoning about the problems of induction would be quite impossible.⁹

It does not, finally, come as a surprise that methodological reflection within physics degenerates to a point where Wigner writes in his well-known essay: “The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift we neither understand nor deserve” (1960, 306). At the beginning of the 1990s, Wigner's paper experienced a renaissance (Mickens 1990). The contributors to Mickens' collection of papers quite cheerfully apply Wigner's thoughts to new areas. Hence the miracle prevails, but not the miracle of mathematics working well for modern physics or other disciplines attempting to profit from a physical approach. The prevailing miracle is that Wigner's declaration of methodological and epistemological bankruptcy has not yet thrown physics into its most fundamental conceptual crisis, the need for which it may still not understand – but which it very well deserves.

⁹ Theory of science also appears to be quite untroubled by the fact that the equivalence of inert and heavy mass, i.e. the *conditio sine qua non* of mechanics as we know it (see above), was put under experimental scrutiny by Eötvös (1890) and others – as if the rock upon which modern physics rests were not Galileo's axiom that all things, if considered as bodies, fall at the same speed.

6 Conclusion

In this paper I have attempted to show three things:

1. The key concepts of modern physics are operational concepts that epistemically level ontologically complex areas in a way that opens these areas up for quantitative exploration.
2. On the basis of such concepts, the regularities to which human interaction with nature is subject can be quantitatively explored.
3. It is central to the identity of physics as a discipline that the regularities of human interaction with nature are mistaken for laws of nature.

To sum up: From the beginning, the business of modern physics has been about eliminating the very conceptual structures that we as societal beings employ to make sense of reality. To make up for this, modern physics constitutes an approach to nature that puts humans at the center, as experimental agents, but, at the same time, completely removes the part we play as agents from methodological reflection as well as from theory formation. From this I conclude that modern physics is indeed neither about us nor about nature.

Reference List

- Aristoteles Latinus. *Physica*. Eds. Fernand Bossier and Jozef Brams. Leiden and New York: E. J. Brill, 1990.
- Carnap, Rudolf. *Physikalische Begriffsbildung*. Karlsruhe: WBG, 1966 [1926].
- Drake, Stillman. *Galileo at Work: His Scientific Biography*. Chicago: The University of Chicago Press, 1978.
- Ehlich, Konrad. "Medium Sprache." *Sprache und sprachliches Handeln*. Vol. 1. Ed. Konrad Ehlich. Berlin and New York: De Gruyter, 2007 [1998]. 151–165.
- Ehlich, Konrad, and Jochen Rehbein. *Muster und Institution: Untersuchungen zur schulischen Kommunikation*. Tübingen: Narr, 1986.
- Eötvös, Roland von. "Über die Anziehung der Erde auf verschiedene Substanzen." *Mathematische und Naturwissenschaftliche Berichte aus Ungarn* 8 (1890): 65–68.
- Galilei, Galileo. *Discorsi e Dimostrazioni matematiche, intorno à due nuove scienze*. 2nd ed. Florence: Barbèra, 1965 [1637].
- Galilei, Galileo. *Two New Sciences*. Transl. Stillman Drake. Wisconsin: University of Wisconsin Press, 1974.
- Heisenberg, Werner. *The Physical Principles of the Quantum Theory*. Chicago: The University of Chicago Press, 1930.
- Hempel, Carl Gustav. *Fundamentals of Concept Formation in Empirical Science*. Chicago: University of Chicago Press, 1952.
- Hempel, Carl Gustav. *Philosophy of Natural Science*. Englewood Cliffs: Prentice-Hall, 1966.

- Janich, Peter. "Wissenschaftstheorie zur Bestätigung der Naturwissenschaften?" *Vernünftiges Denken: Studien zur praktischen Philosophie und Wissenschaftstheorie*. Eds. Jürgen Mittelstraß and Manfred Riedel. Berlin and New York: De Gruyter, 1978.
- Kant, Immanuel. *Kritik der reinen Vernunft*. Hamburg: Meiner, 1990.
- Koyré, Alexandre. "An Experiment in Measurement." *Proceedings of the American Philosophical Society* 97 (1953): 222–237.
- Lagrange, Joseph Louis. *Mécanique Analytique*. Eds. Joseph Serret and Gaston Darboux. 4th ed. Paris: Gauthier-Villars, 1888 [1788].
- Lakoff, George, and Mark Johnson. *Metaphors We Live By*. Chicago: University of Chicago Press, 1980.
- Maier, Anneliese. *Metaphysische Hintergründe der spätscholastischen Naturphilosophie*. Rome: Storia e letteratura, 1955.
- Mickens, Ronald E. (ed.). *Mathematics and Science*. Singapore: World Scientific, 1990.
- Newton, Isaac. *Philosophiae naturalis principia mathematica*. Eds. Alexandre Koyré and I. Bernhard Cohen. 3rd ed. Cambridge: Cambridge University Press, 1972 [1726].
- Popper, Karl Raimund. *The Logic of Scientific Discovery*. London: The Anchor Press, 1977 [1935].
- Popper, Karl Raimund. *Quantum Theory and the Schism in Physics*. London: Hutchinson, 1982.
- Thielmann, Winfried. *Fachsprache der Physik als begriffliches Instrumentarium – exemplarische Untersuchungen zur Funktionalität naturwissenschaftlicher Begrifflichkeit bei der Wissensgewinnung und -strukturierung im Rahmen der experimentellen Befragung von Natur*. Frankfurt a. M.: Lang, 1999.
- Thielmann, Winfried. *Deutsche und englische Wissenschaftssprache im Vergleich: Hinführen – Verknüpfen – Benennen*. Heidelberg: Synchron, 2009.
- Wierzbicka, Anna. *Lexicography and Conceptual Analysis*. Ann Arbor: Karoma, 1985.
- Wigner, Eugene P. "The Unreasonable Effectiveness of Mathematics in the Natural Sciences." *Mathematics and Science*. Ed. Ronald E. Mickens. Singapore: World Scientific, 1990 [1960]. 291–306.
- Wright, Georg Henrik von. "On the Logic and Epistemology of the Causal Relation." *Causation and Conditionals*. Ed. Ernest Sosa. Oxford: Oxford University Press, 1975. 95–113.