

Idealizations in Physics

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Abstract

In this chapter, I differentiate among several forms of idealization employed in the physical sciences. Drawing on current discussions in the philosophy of science, I maintain that these various idealizations play distinct epistemic roles in physics and are, therefore, justified differently. I then examine how the use of idealizations is connected to other major debates in the philosophy of science, such as reductionism and scientific realism.

Key Points

- different types of idealization used in physical sciences.
- various philosophical problems that arise from employing idealizations in physics.
- the relationship between the use of idealizations and other important topics in philosophy of science, such as inter-theoretic reduction.
- various strategies proposed in philosophy for reconciling the use of idealizations with scientific realism.

1 Introduction

*Had we but world enough and time,
This coyness, lady, were no crime.
We would sit down, and think which way
To walk, and pass our long love's day.
-Marvell, To His Coy Mistress*

At the opening of his poem “To His Coy Mistress,” Andrew Marvell contrasts an idealized world in which he and his beloved have unlimited time together with the actual world, where time rushes by a dizzying speed. The fact that time passes is evident not only to Marvell, but also constitutes one of our most basic perceptual experiences. We see each day come to an end as another begin, and we see children grow while we ourselves age. Even for an artist is hard to create a fictional world in which time stays still or passes infinitely slowly, and only a few of them have attempt to propose so. John Cage’s composition “4’33’,” characterized by silence, is one example of this. Another is his work “As Slow as Possible,” a piece planned to be performed over 639 years—far too slow to be fully heard or appreciated by humans, whose lifespans are confined to a much shorter time scale.

What is striking is that, even though we clearly experience time as passing at an apparently accelerated pace, the idea of processes unfolding infinitely slowly extends beyond the realm of avant-garde musical experiments. Indeed, it constitutes one of the most important *idealizations* in physics, which are defined as intentional *distortions* of the systems under investigation (Weisberg, 2007). In thermodynamics, the assumption of processes occurring infinitely slowly plays a crucial role in the notion of reversible processes. Similarly, in statistical mechanics, the assumption of an infinite time is required to give a rigorous definition of *ergodicity*, a concept that is useful to define equilibrium. Treating time as infinite is just one among many

idealizations employed in all areas of physics, where is common to hear about frictionless planes, objects in free fall without air resistance, teacups containing an infinite number of molecules, and fire walls situated at the boundaries of black holes.

From a philosophical point of view, the use of idealizations in physical theories is puzzling. On the one hand, many of us are realist with respect to science, in the sense that we believe that science, and especially physics, is supposed to tell us a true (or approximately true) story about the world in which we live in (Godfrey-Smith, 2006). On the other hand, it is not immediately clear why distorting the target systems can result in scientific theories and models that are empirically successful. For many years, it was believed that idealizations had a pragmatic justification in the sense that they were introduced to facilitate mathematical calculations (McMullin, 1985). In this view, idealizations should be better understood as *approximations* to the systems under study and would tend to disappear as science progresses. However, in recent years, especially after the publication of Weisberg's paper "Three kinds of Idealizations" (Weisberg, 2007), philosophers started to recognize other types of idealizations with different justifications and different epistemic goals. In this view, not all idealizations have a pragmatic role and not all idealizations should be interpreted as approximations to the target systems. In this chapter, I adopt this pluralistic perspective on idealizations by broadening Weisberg (2007) classification in light of recent work in the philosophy of physics. Instead of distinguishing between three kinds of idealizations, I will distinguish between six types of idealizations, each of them with a different epistemic role and justification. I will then discuss the extent to which such idealizations challenge inter-theoretic reduction and scientific realism.

2 Galilean Idealizations

For McMullin (1985), "Galilean idealization" is an umbrella term that covers several types of idealization, including mathematical; constructive; and causal idealizations. What all these idealizations have in common is that each deliberately reduces something complex (a situation, a concept, etc.) to a simpler form. Another feature they share is that they all emerged within Galileo's new science, which rested on the mathematization of physics.

One of the most important "Galilean idealizations" are *mathematical idealizations*, which can be understood as imposing a mathematical formalism on a physical situation, in the hope that the essentials of that situation will be suitable of mathematical representation (McMullin, 1985). Formulating physics in mathematical terms implied for Galileo setting aside the qualitative specifics of particular systems so that we can achieve a more general and abstract understanding of nature. In other words, it involves necessarily the appeal to idealizations. An illustration of this is the way the laws of motion were derived by Galileo, namely by isolating specific causes and, in doing so, by abstracting from details deemed insignificant. In this way, idealization is seen as a method for revealing general laws and for identifying the actual motion that nature uses to make bodies fall.

In his work "Two New Sciences" (Galilei, 1974), Galileo presents potential objections to this kind of idealization through the character of Simplicio, the representative of the Aristotelian tradition. Simplicio argues that mathematical idealizations tend to falsify the real world which is not neat and regular. As a consequence, he points out that mathematical idealizations may do very well in the abstract, but they will not work out when applied to sensible and physical matters. Salviati, acting as Galileo's spokesman, defends the use of mathematical idealizations against Simplicio's objections by arguing that scientific accuracy requires separating theoretical principles from material imperfections. Simplicio's objections were then echoed by Husserl (1936), who argues against the use of this type of idealization or, what he called "the Galilean program", by arguing that they performed a "surreptitious substitution" of a geometrically prefigured world for the real world of our experience.

Another type of idealization used by Galileo are *constructive idealizations*, which can be understood as a special class of mathematical idealizations that were discussed above. These idealizations consist of focusing on a simpler analogue (or model) of the original system, which allows one to solve a problem more easily. The assumption of frictionless planes or perfectly spherical rolling balls are examples of this type of idealization. Since constructive idealizations characterized Galilean style, they are normally referred to in the philosophical literature as "Galilean Idealization". Galileo justified the use of these idealizations pragmatically, by arguing that the departure from truth is imperceptibly small and yet the idealization enables mathematical calculations that would otherwise be impossible or at least very complicated. An example of this is when we calculate the distance reached by a projectile, by assuming that the Earth is flat. Such an idealization allows one to compute more easily the downward effect of weight, without having to take into account perturbations in the trajectory caused by the curvature of the planet. In mundane cases, when the distance traveled by the body is small relative to the size of the Earth, this can be shown to be a very good approximation to realistic trajectories.

Constructive idealizations can be further divided into *formal* and *material* idealization, depending on how much detail was taken into account in the original idealization. Formal idealizations abstract away irrelevant details. An example discussed by McMullin (1985) is Newton's model of the solar system. Newton recognized that the Earth's gravitational field should cause the Sun to move slightly. Nevertheless, he treated the Sun as if it were at rest, which, within his theoretical framework, was equivalent to assuming it had an infinite mass. This simplification made it much easier to derive the laws of motion, although it implied that the results were, as we know now, only approximations of the phenomena. *De-idealizing* this model consisted in "adding back" details that were left out in the original idealization, for instance about the effects of the Earth and other planets upon the Sun, which can be done systematically by correcting the theoretical laws or models in light of empirical evidence. In this framework, it is assumed then that de-idealizations delivered more accurate models, and that as science progresses, this type of idealizations will tend to disappear.

Another example of formal idealizations mentioned by McMullin (1985) is the ideal gas law or Boyle-Charles Law: $PV = nRT$, where P is pressure, V is the volume, n is the number of moles of gas, R is the ideal gas constant, and T is the Temperature. This law was derived by assuming that the particles of a gas were perfectly elastic spheres whose volume was negligible compared to the volume occupied by the gas and whose mutual attractions can also be neglected. De-idealizing this law consists of including theoretical corrections that make the model more accurate, especially in cases where the model does not give a good approximation, such as cases of high pressures and very small volumes. For instance, if one allows for space occupied by the molecules or for the small attractions between them, one arrives at a new theoretical law in which both the volume and pressure factors are slightly amended in comparison to the ideal law. In this case, we can use the Van der Waals's equation: $(P + an^2/V^2)(V - nb) = nRT$, where an^2 is the pressure correction, and nb is the volume correction. This gives a much better description of the behavior of gases at high pressures than the original law of ideal gases.

As mentioned above, an important feature of formal idealizations is the assumption that the model will improve by *de-idealizing it*: "if simplifications have been made in the course of formulating the original model, once the operations of this model have been explored and tested against experimental data, the model can be improved by gradually adding back the complexities." (McMullin, 1985, p. 261). This will mark an important difference with respect to minimal idealizations discussed in Section 3.

Other type of constructive idealization are *material idealizations*. The term originates from Aristotle's notion of material cause and designates explanations that rely solely on what something is made of, leaving all other aspects unspecified. For material idealizations the "material" can be purely conceptual serving as a conceptual boundary within which subsequent theoretical developments can be framed. An example of a material idealization is when we appeal to an entity without specifying its inner structure. For instance, in Rutherford's model of the atom, the "blank" nucleus is idealized in the sense of being left unspecified. According to McMullin (1985), this blank functions as the "material" from which an explanation of the scattering experiments can be built. This type of idealization has a pragmatic role in the sense that it facilitates understanding. As in the case of formal idealization, it is assumed that the model will improve by adding further specifications of the objects that are being idealized, for instance, by giving information about protons and neutrons. The difference between formal and material idealizations lies in how we de-idealize the model. Whereas de-idealizing the first implies adding corrections to the original calculations, de-idealizing the latter means filling in information that was left out.

Another type of Galilean idealization is *causal idealization*, which McMullin (1985) defined as isolating the different causes leading to a certain phenomenon. Galileo's insight, which was at the core of his mathematization of science, was that complex causal situations can only be understood by first taking the causal lines separately and then combining them. For Galileo, the unordered world of nature was a "tangle" of causal lines and there was no hope of a "firm science" unless one could in some way simplify this tangle by removing those causal factors that obstruct or complicate the effects one is attempting to isolate. For Galileo, this kind of idealization is not artificial, but instead it allows us to understand real behavior without impediments or distorting factors. In this sense idealizing the system helps uncovering something real about how objects actually move. In this view, Galileo departs radically from Aristotle's conception, in which this sort of simplification appeared suspicious because order was imposed artificially. In fact, Aristotle had argued that a vacuum is impossible in nature and hence that air resistance is necessarily a retarding factor that should be included to describe motion. On the contrary, the logic of Galileo's argument led him to separate the real causes from distorting factors, such as air resistance, and to conclude that all bodies in the void fall at the same speed. What he wanted to discover was the "downward tendency which (body) has from its own heaviness" (cited in McMullin (1985, 297)) in the absence of all other causes.

Causal idealizations are very similar to what contemporary philosophers of science have dubbed as "minimal idealizations" that we describe in the next section. Perhaps the main difference between Galileo's conception and the contemporary discussion is the focus of the latter on representational models.

3 Minimal and Minimalist Idealizations

An important part of the contemporary discussion on idealizations in physics focuses on the use of idealizations in the context of *scientific representational models*. Representational models are tools, such as physical or conceptual structures, that allow researchers to represent complex target systems in the real world (Frigg and Hartmann, 2006). An influential view on models in philosophy of science interprets them as *mediators* between the theory and the phenomena that are observed in nature (Morgan and Morrison, 1999). An example is Ehrenfest model of the atom or the Ising model in condensed matter physics to study the phenomenon of ferromagnetism. Weisberg (2007) famously distinguishes between three types of idealizations used in representational models. The first is what he calls "Galilean idealization," which corresponds to what McMullin (1985) dubbed as "constructive idealization". Another type are "multiple models idealizations" that we will explain in the Section 4. Finally, there are "minimalistic idealizations" that we will discuss in this section.

A *minimalist idealization* is the practice of constructing theoretical models that include solely the core *causal factors* which give rise to a phenomenon. For Weisberg (2007), a minimalist model contains only those factors that make a difference to the occurrence of the phenomenon in question. Unlike constructive idealizations, these idealizations are not justified pragmatically, as tools for making mathematical problems more manageable, but instead are justified as a means of enhancing the model's explanatory power. Also, in contrast to constructive idealizations, it is not expected that these models will be improved by future

de-idealizations. On the contrary, making the model more realistic and incorporating additional details can actually reduce its explanatory power. This implies that such models are not necessarily responsive to the current state of a given science and may not improve as that science progresses.

An example of a minimalist model is the Ising model, which was originally developed to study the transition in magnetic materials from paramagnetism, where the material does not have magnetization, to ferromagnetism, in which there is magnetization, by decreasing the temperature. The model tries to capture the main factors leading to this transition, by assuming that the spins are fixed in a lattice and only interact with their nearest neighbors. The transition to ferromagnetism thus arises from neighboring spins imitating one another, a process that propagates throughout the whole system and ultimately produces collective alignment. In more detail, the Hamiltonian of the Ising model is defined as follows:

$$H = -J \sum_{\langle ij \rangle} S_i S_j - h \sum_i S_i, \quad (1)$$

where S_i is the Ising spin ($S_i = \pm 1$) at site (lattice site) i , and $\langle ij \rangle$ represents an interacting spin pair. The coefficient J is the interaction constant (coupling constant) and h represents the external magnetic field expressed in units of energy in magnetic materials. In two dimensions, the Ising model can be thought of as an array of spins on a square lattice (Fig. 1).

For Weisberg, this is an example of a minimalistic model, because the model isolates the main causal factors leading to the transition, leaving out all irrelevant factors, including the particles' motion. In this case, the transition is simply explained as the result of a cascading imitation procedure between spins, which spreads through the entire system, leading to a phase transition.

Batterman and Rice (2014) interpret these highly idealized models, which they dubbed as "minimal models", as simplified mathematical models that capture macroscopic behaviors by deliberately omitting micro-level causal mechanisms. In contrast to Weisberg (2007), they do not think that minimal models, like the Ising model, represent the core causal factors leading to a certain phenomenon, but rather capture the universal large-scale properties observed in a class of diverse systems. This is also the argument that they use to explain why highly idealize models, such as the Ising model, can be used to describe diverse phenomena, from ferromagnetism to the water-vapor transition.

By discussing the Johansen-Ledoit-Sornette (JLS) model, an econophysics model that aims to explain market crashes by relying on the physics of phase transitions, Jhun *et al.* (2018), argue that minimal models can be used both to explain the core causal factors leading to a certain phenomena, or to explain why different systems exhibit the same macro-behavior. The type of explanation that minimal models provide, depends for them on the research question at stake. If the modeler's research question is why there is universal behavior, one can appeal to the structural large-scale properties that are observed in the entire class of systems exhibiting the same behavior, i.e. the *universality class*. On the other hand, if the question is why there is a transition in a particular system, the same model can be used to identify the core causal factors of that particular domain, in line with Weisberg's view (Weisberg, 2007).

What all these approaches to minimal models have in common is the idea that one of the most important epistemic functions of these models is to provide explanations, and that simply adding more detail to a model does not necessarily enhance its explanatory power.

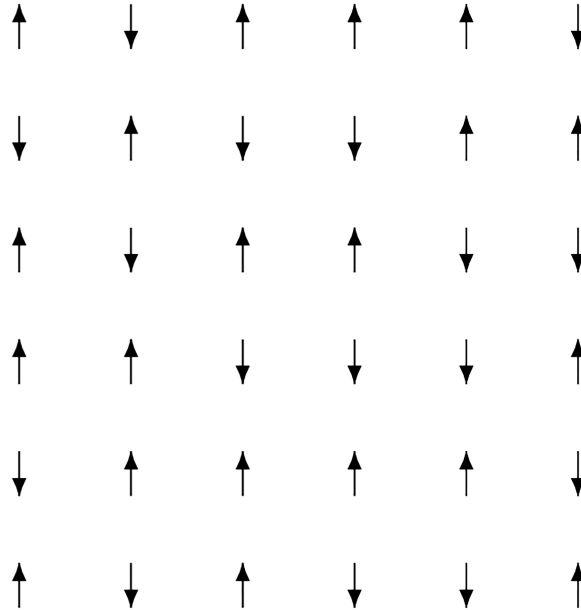


Fig. 1 Representation of the two dimensional Ising model with square lattice.

4 Multiple Models Idealizations

Weisberg (2007) defines *multiple models idealizations* as the practice of using multiple models that are related but strictly speaking incompatible, in the sense that each of them makes different claims about the nature and causal structure giving rise to a certain phenomenon. The example he gives is the United States National Weather Service, which uses three incompatible models of global circulation patterns to model the weather. Each of these models contains different idealizing assumptions about the basic physical processes involved in weather formation. For instance, one of them assumes that the Earth does not rotate whereas the others relax this idealization. Another example in physics is the combination of different scalar models to explain properties of fundamental particles. Scalar models are mathematical frameworks that are invariant under coordinate transformation. They are called “scalar models” because they involve spin-0 fields that assign a single, directionless value to every point in space and time. In quantum versions of these models, tracking interactions often leads to mathematical infinities (ultraviolet divergences), which are mathematically untreatable. Klauder (2017) shows how combining different incompatible scalar models (renormalizable, strictly renormalizable and non-renormalizable) can help deal with these infinities without triggering mathematical breakdown.

Weisberg (2007) justifies the use of multiple models in science by the existence of tradeoffs among epistemic virtues. He notices that scientists have different epistemic virtues in mind when they construct their scientific models, such as accuracy, precision, generality and simplicity. He then argues, in the same vein as Levins (1966), that these different epistemic goals can trade off with one another in certain circumstances, meaning that no single model can have all of these properties to the highest degree. The use of different incompatible models is thus understood as a strategy for attaining sufficiently high degrees simplicity, generality and precision without needing to sacrifice one in order to enhance the others. The use of different incompatible models in the United States National Weather Service can be seen then as a strategy to capture large-scale patterns of atmospheric circulation through global models and localized phenomena such as thunderstorms through high resolution models. In the case of quantum field theory, the use of incompatible scalar models with different renormalizability properties can be interpreted as a strategy to dealing with the problem of ultraviolet divergences (Klauder, 2017).

Lisciandra and Korbmacher (2021) have recently discussed the use of multiple models in the context of international trade-theory and have shown how in some cases, different models can lead to one consistent explanation. This is possible, according to them, when the different models despite making different assumptions about the target system, have a common structure. However, the extent to which this applies to the use of multiple models in physics remains to be investigated.

5 Essential Idealizations

In philosophy of physics, philosophers have distinguished between *essential* and non-essential idealizations. Essential idealizations are commonly defined as idealizations that are indispensable to the explanation of a phenomenon P , meaning that the explanation of P disappears as soon as the idealization is relaxed (Batterman, 2002; Butterfield, 2011; Norton, 2014; Palacios, 2022; Palacios *et al.*, 2021; Shech, 2018). On the other hand, non-essential idealizations can typically be de-idealized without the theory losing its capacity to explain the phenomenon. The most discussed cases of potential essential idealizations are *infinite idealizations* in the form of mathematical limits. An infinite limit consists in taking the value of a quantity to infinity, such as time $t \rightarrow \infty$ or the number of particles $N \rightarrow \infty$. In some cases, appealing to infinite limits can be straightforwardly interpreted as a constructive idealization, since they are used with the purpose of making the mathematical description of physical phenomena more tractable, but can be de-idealized. However, in some cases, the use of infinite limits seems necessary in order to attain agreement with empirical results, such as the case reversible processes in thermodynamics, phase transitions in condensed matter physics, and symmetry-breaking in high energy physics.

If the limit can be straightforwardly interpreted as an approximation to the target system, the limit is called “regular” (Batterman, 2001). An example is in special relativity when the limit $v \rightarrow 0$ (or $(v/c)^2 \rightarrow 0$) is used to recover the laws of classical mechanics. More in detail, the limit of the Lorentz factor γ as the velocity v goes to 0 (or c goes to ∞) is 1, and its behavior at low speeds is approximated by the Taylor series:

$$\gamma(v) = \frac{1}{\sqrt{1 - (v/c)^2}} = \sum_{n=0}^{\infty} \left(\frac{v}{c}\right)^{2n} \frac{(2n-1)!!}{2^n n!} = 1 + \frac{1}{2}(v/c)^2 + \frac{3}{8}(v/c)^4 + \dots$$

Since we can quantify the degree of distortion by considering the terms of the series expansion that has been included, this limit can be straightforwardly interpreted as an approximation to the realistic behavior of the system. In many cases, it is assumed that the more terms of the series one takes into account the more accurate the representation (Palacios, 2018; Batterman, 2001).

To differentiate between instances of infinite limits that can be easily understood as approximations and those that are “essential idealizations”, Butterfield (2011) notices that there is a crucial difference between “the limit of a sequence of functions” and “what is true at that limit”: that is, respectively,

- the limit f_{∞} of the sequence $f_1, f_2, \dots, f_n$ of functions, and
- the function $f_{S_{\infty}}$ associated with the limit system S_{∞} .

Idealizations that can be demoted to approximations are cases in which (i) and (ii) are well defined and equal, whereas cases of essential idealizations are cases in which (i) and (ii) are well defined but not equal, and (ii) rather than (i) is empirically correct.

Intuitively, essential idealizations are puzzling. We usually think of idealizations as “distortions” of what we actually observe. So why is it that models derived by taking a limit end up being more empirically accurate than models from which the idealizations have been removed? [Palacios et al. \(2021\)](#) reconstruct this mystery as the result of the following paradox, which they call the “Paradox of Infinite Limits”:

Suppose that in order to represent a physical phenomenon P we define a system of the form S_n , then the Paradox of Infinite Limits can be essentially formulated as a combination of the following statements:

- (1) Finiteness of Real Systems: If S_n represents a real system, then the variable n corresponding to some physical parameter cannot take on infinite values.
- (2) Indispensability of the Limit System: The explanation of the phenomenon P can only be given by means of claims about an infinite system S_∞ constructed in the limit $n \rightarrow \infty$.
- (3) Enhanced Indispensability Argument (EIA): If a claim plays an indispensable role in the explanation of a phenomenon P we ought to believe in its existence.

[Palacios et al. \(2021\)](#) point out that the resolution of the paradox will depend on the case study and the statement that we are willing to give up. One of the controversial cases is the case of phase transitions, which are those sudden changes observed when water boils. In thermodynamics, these types of changes are defined as discontinuities in the derivatives of the free energy and this description is empirically correct ([Palacios, 2019](#)). The problem is that in order to recover this behavior in the microscopic theory of statistical mechanics, one has to take the thermodynamic limit, whereby the number of particles and the volume of the system go to infinity. According to [Batterman \(2001\)](#), this is a case of essential idealizations, where the model obtained by taking the infinite limit is empirically accurate, whereas the de-idealized model is not. This means that we should give up statement (1). Other authors ([Butterfield, 2011](#); [Norton, 2014](#); [Palacios, 2019](#); [Wu, 2021](#)) have argued, however, that this is a case of idealizations that can be interpreted as approximations, showing that the model gives empirically correct results also for finite values of N , or “on the way to the limit.” According to them, the statement that should be then given up in the reconstruction of the paradox is (2) (See also [Section 6](#)).

Although [Butterfield \(2011\)](#) conjectures that infinite idealizations can be interpreted as approximations more generally. Some philosophers have shown that matters are less straightforward in other cases. [Landsman \(2013\)](#) argues, for example, that the case of spontaneous symmetry breaking in quantum systems is less straightforward than classical phase transitions, and consequently it is harder to show that finite systems can exhibit the same behavior that appears at the limit. In spite of this, he shows that for large-but-finite systems, symmetric ground states become exponentially unstable to microscopic, asymmetric perturbations. As a result, the system dynamically settles into a broken-symmetry state even before the infinite limit is actually reached.

Another controversial case of infinite idealizations is the use of the infinite-time limit, where time t goes to infinity. [Norton \(2014\)](#) has argued that the use of the infinite-time limit to account for reversible processes is not even an idealization, since it leads to paradoxes in thermodynamics. More in detail, he argues that there are two sufficient conditions under which an approximation cannot be promoted to the status of idealization, which are closely related to the formal conditions mentioned earlier: (1) the limit system does not exist in the sense that it is paradoxical, and (2) the limit system has properties that are inadequate for the idealization in that they do not match with the properties of the finite target system. In the case of reversible processes, it is the first condition the one that is not satisfied. He argues that for a process to be reversible, driving forces must be infinitesimal, which means the process takes infinitely long to complete. In the limit where time approaches infinity, many time-dependent thermodynamic laws break down or yield indeterminate, leading to paradoxes, such as passing heat with a temperature difference of zero. As a result, Norton concludes that this is a case of approximation without idealization. However, [Valente \(2019\)](#) argues against this conclusion, showing that this paradoxical character disappears if one assumes the notion of quasi- processes introduced by [Ehrenfest-Afanassjewa \(1956\)](#). This allows for an interpretation of the infinite-time limit in the account of reversible processes as an idealization that can be demoted to an approximation.

Another case is the use of infinite-time limit in physics is the assumption of ergodicity in statistical mechanics. In this theory, one distinguishes between phase- averages, which is the average over all possible microscopic states of a system, and time-averages, which is the average of the behavior of a single trajectory over an infinite timeline. The ergodic hypothesis says that if we let time go to infinity, the system will eventually explore all possible regions of the phase space. If the system is ergodic, then the phase average and the time average coincide and one can relate the quantities in statistical mechanics with observations. [Palacios \(2018\)](#), pointed out that in contrast to first order phase transitions, in this case one cannot justify the use of the limit, by demonstrating that approximately the same behavior that occurs in the limit, also occurs “on the way to the limit.” The problem is that the expected behavior that allow us to relate phase averages with time averages arises for finite but unrealistic values of t . Indeed, even in simple examples like a small sample of diluted hydrogen, one can estimate that the desired behavior can occur for times that are finite but unimaginably longer than the age of universe. In such cases, even if we can actually demonstrate that the behavior arises for finite values of t , we would not have succeeded in demonstrating the empirical adequacy of the theory, and therefore, would not succeed in justifying the use of the limit.

6 Non-Representational Idealizations

Most of the idealizations discussed above occurred in representational models, which are designed to mediate between a scientific theory and a phenomenon. Yet, one needs to bear in mind that idealizations are not always representational. For example, they can play a role in thought experiments, which are fictional scenarios that occur in the laboratory of the mind (El Skaf and Stuart, 2024). Maxwell's demon, proposed by James Clerk Maxwell in 1867, is a paradigmatic example of such experiments. This experiment postulates a small being, called later a "demon," which can manipulate the flow of gas molecules in a container without expending energy. He does so by controlling a door that divides the container into two parts. One assumes then that when the gas molecules approach the door, the demon can quickly select the molecules allowing only fast-moving molecules (which produce hot temperatures) to pass from the left- to the right-hand side of the container and allowing only slow-moving molecules (which produce cold temperatures) to move from right to left. By doing this, the demon is able to make one part of the container colder as the other gets hotter. Importantly, this implies that temperature differences could be produced at the expense of no work and that entropy can also decrease in the process, thus violating the second law of thermodynamics. According to El Skaf (2021), the principal epistemic function of such thought experiments is not to represent a realistic behavior, but to reveal inconsistencies between different theoretical statements. In this case, an inconsistency is revealed between the deterministic formulation of the second law of thermodynamics and the laws of classical mechanics, assumed to govern the behavior of particles. In El Skaf and Palacios (2022), this conclusion is extended to thought experiments used in the context of black hole physics. Bokulich (2001) has also defended a similar interpretation of thought experiments by arguing that their principal function is not to represent a phenomenon, but to test the non-empirical virtues of a theory, such as consistency and explanatory power.

In the case of Maxwell's thought experiment, the non-representational function of idealizations taken place in thought experiments is particularly clear. The demon here is not meant to represent a realistic being, but rather to make the problems with the second law more intuitive. We may have recognized those potential violations of the second law without bringing demons into the story, but these imaginative scenarios helped scientists grasp the issues with the second law more intuitively. There is therefore no de-idealization needed in these cases of idealizations and they should not be justified as being approximations of real behaviors. On the contrary, substituting these types of idealizations with a more realistic assumption can actually make the contradiction less evident and the thought experiment may lose its epistemic function (El Skaf and Palacios, 2022).

Like minimal models idealizations, non-representational idealizations are not expected to be de-idealized as science progresses. However, unlike the former, the latter are not required to be empirically correct, not even approximately. Their legitimacy stems from their role in exposing inconsistencies or other non-empirical virtues of scientific theories, something they can achieve even when they involve purely fictional entities, such as the demon in Maxwell's case.

7 Idealization and Reduction

An issue of intense debate in the philosophy of science is whether idealizations pose a challenge for *inter-theory reduction*, which occurs when a theory reduces to another. There are different models of inter-theory reduction (Palacios, 2024), but the most important ones are the Nagelian model, proposed by Nagel (1961), and Nickles' model of limiting reduction, proposed by Nickles (1973). According to the Nagelian model, a theory T_2 reduces to another one T_1 , if and only if T_2 can be logically deduced from T_1 plus auxiliary assumptions. In cases of *heterogeneous reduction*, one also needs to construct *bridge laws* that connect the vocabularies of both theories. A paradigmatic example of Nagelian reduction is the reduction of Galilean law of free fall to Newton's law of universal gravitation. If we assume that the distance of the falling object to the surface of the Earth is negligible, compared to the radius of the Earth, we can deduce Galilean law of free fall that asserts that the objects fall with constant acceleration g . According to Feyerabend (1981), however, although there may be a numerical approximation in both theories, there is semantic incommensurability between them, which blocks reduction. He stresses that in Galilean theory, acceleration is a kinematic state of change used to describe motion, whereas in Newtonian theory acceleration is the dynamic result of an impressed force $F = ma$. This difference in meaning leads to a logical inconsistency between the two theories which naturally impedes the logical deduction from one to the other. Although it is widely recognized that this type of inconsistency poses a problem for Nagelian reduction in the strictest sense, most philosophers, including Nagel himself (1972), believe that this problem vanishes if we consider a weaker form of reduction that admits approximations (Butterfield, 2011; Chen, 2025; Nagel, 2008; Palacios, 2024).

Limiting reduction differs from Nagelian reduction in that logical deduction may play no role in the derivation of one theory from another. This type of reduction occurs when we can obtain T_2 by applying a mathematical transformation, more specifically a mathematical limit, on the relevant quantities of theory T_1 . According to Palacios (2024), limiting reduction should satisfy two conditions, which are implicit in Nickles' approach: (i) Convergence: $\lim_{x \rightarrow \infty} T_1 = T_2$, (ii) Physical significance: the limiting operation makes physical sense. Batterman (2001) famously argued that regular limits do not pose a challenge for reduction because there is convergence of the relevant quantities to the limit values, which means in Palacios' framework that they satisfy condition (i). An example is the reduction of Newtonian theory to Einstein special theory of relativity SR described in Section 5. In this case, the quantities of SR can be written as Newtonian or classical quantities plus an expansion of corrections in powers of $(v/c)^2$. So one can quantify the degree of approximation in the quantities of both theories and, furthermore, reconstruct the

relationship between SR and Newtonian theory as a regular perturbation problem. In this case, also condition (ii) is satisfied, because the limit $(v/c) \rightarrow 0$ of low velocities is physically plausible. In fact, this limit can be naturally interpreted as a constructive idealization, where the departure from SR (which we regard as more accurate than Newtonian mechanics) becomes arbitrarily small. The velocity of the particles or the object falling to the surface of the Earth may not be zero from the perspective of SR, but it is negligible compared to the speed of light.

Matters are much more challenging, however, in the case of “singular limits,” which are cases in which the behavior at the limit is qualitatively different from the behavior close or “on the way” to the limit (Batterman, 2002; Butterfield, 2011; Palacios *et al.*, 2021). Apparently, these cases violate condition (i) of limiting reduction, since they cannot be straightforwardly reconstructed as series expansions. A paradigmatic example is the case of first-order phase transitions which are rigorously defined in terms of discontinuities in the derivatives of the free energy. Since this behavior only appears in the thermodynamic limit $N/V \rightarrow \infty$ and disappears as soon as we move away from the limit, Batterman (2001) argues that this is a case of essential idealization, which implies a failure of both Nagelian and limiting reduction. Moreover, because what happens exactly at the limit, rather than merely near to it, is empirically adequate, he contends that this feature is characteristic of emergent behavior, which is described in terms of singular limits.

Despite the influence of Batterman’s view, several philosophers (e.g., Butterfield, 2011; Fraser, 2016; Norton, 2014; Palacios, 2019; Wu, 2021) have argued that many cases considered by Batterman, including the case of first and second order phase transitions, can be given a deflationary interpretation, which is consistent with limiting reduction, or even Nagelian reduction. The main argument, proposed originally by Butterfield (2011) is that if we focus on the relevant quantities, such as magnetization in the paramagnetic-ferromagnetic transition, we will find that the behavior “on the way to the limit” approximates the behavior at the limit. Furthermore, it is shown that the former behavior instead of the behavior at the limit is empirically correct. This means that the conditions of limiting reduction are satisfied and that we can interpret this idealization as a case of constructive (Galilean) idealization instead of as a case of essential idealization. Although this later solution has been applied to different case studies, it remains the question of whether other apparent cases of essential idealizations, in particular in quantum mechanics and high energy physics, can be given the same solution (Palacios *et al.*, 2021; Ruetsche, 2011). This suggests that the extent to which putative cases of essential idealizations pose a challenge for inter-theory reduction should be analyzed on a case-by-case basis, and that the question of whether idealizations pose a challenge for reduction is still an open problem in science and philosophy.

8 Idealizations and Scientific Realism

Scientific realism has been defined in several different ways, but most philosophers take it to be the position that scientific theories- or at least some of their parts- “are true or approximately true (Chakravartty, 2011). Based on this definition, the use of the different types of idealizations seems to be at odds with a realistic view of science.

In her seminal work “How the Laws of Physics Lie” Cartwright (1983) examines how scientific models and theories rely on idealizations, which leads her to defend an antirealist interpretation of science. Her main thesis is that the theoretical laws of physics, despite their claims to be fundamental truths about the universe, are in fact false. They do have broad explanatory power, but at the price of sacrificing realism. Indeed, idealization in physics, though permissible on pragmatic grounds, is thus not truth-producing. Laws and scientific models are only valid under *ceteris paribus* conditions, which are never satisfied in the real world.

McMullin (1985) focuses on Galilean idealizations to argue against Cartwright’s position. In a similar vein as Galileo, he argues that idealizations are not simply a escape from the intractable irregularity of the real world, but rather a strategy to grasp the real world from which the idealization takes its origin.

A more systematic defense of realism, which considers different types of idealizations, has been given by Weisberg (2007). According to him, the three types of idealizations he considers (Galilean, Minimalistic and Multiple models idealizations) are compatible with a weak version of realism that admits approximations. Galilean idealizations, which correspond to what we have named here “constructive idealizations,” are straightforwardly compatible with realism, because we can quantify the degree of inaccuracy or approximation from the realistic behavior. In fact, the hope is that this type of idealizations disappear as science advances, leading to more accurate models. According to Weisberg, minimalistic idealizations are also compatible with realism, because they capture the true causal factors leading to a certain phenomenon. This has also been defended by Strevens (2011). Finally, he argues that multiple models idealizations are also compatible with realism, because they combine different models that capture different aspects of truth: whereas the minimalistic models involved in multiple idealizations capture real causal mechanisms, Galilean models give a richer description that is also approximately true. Wimsatt (2007), also argued that multiple idealized models are important because they help us develop truer theories.

Butterfield (2011), and Palacios *et al.* (2021) contribute to this discussion by focusing on the case of “essential idealizations,” in particular, infinite limits. According to them, also putative cases of essential idealizations can be given a realist interpretation, if one can show that they can be plausibly interpreted as cases of approximations. The case of phase transitions is an example of this. In contrast, the case of non-representational idealizations, especially the ones occurring in thought experiments can be made compatible with realism, even without appealing to the notion of approximation. Since the idealization does not have the purpose of representing a real phenomenon, the clash with realism takes a weaker form. In fact, we could justify the use of

fictional idealizations, such as demons or firewalls in the horizon of a black hole by arguing that they help uncovering inconsistencies or other epistemic virtues of scientific theories (Bokulich, 2011; El Skaf and Palacios, 2022).

Despite this defense of realism, the issue is still the focus of active philosophical dispute. In particular, the standing of indispensable or essential idealizations that cannot be straightforwardly construed as mere approximations remains controversial (Batterman, 2002; Batterman, 2021; Bangu 2013; Batterman and Rice, 2014; Shech, 2013).

9 Conclusion

The significance of idealizations in physics is among the central issues in the philosophy of science. In recent years, philosophers have pushed this discussion forward by carefully distinguishing various kinds of idealizations, each with its own epistemic justification in scientific practice. In this chapter, I have surveyed this body of work, highlighting the philosophical challenges that emerge when we examine how idealizations are employed in science. In particular, I have shown that the issue of idealizations is inherently connected to debates about reduction and realism. While I have outlined several strategies for addressing the realist worries raised by the use of idealizations, we have also seen that the extent to which idealizations are compatible with reduction or realism has to be evaluated on a case-by-case basis. Instances of idealization in contemporary physics that currently lie beyond experimental access, such as in black hole physics, are especially intriguing and warrant careful examination in order to argue for its compatibility with realism and reduction.

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Further Reading

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