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Guiding principles in physics

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Abstract

Guiding principles are central to theory development in physics, especially when there is only limited empirical input available. Here I propose an approach to such principles looking at their heuristic role. I suggest a distinction between two modes of employing scientific principles. Principles of nature make descriptive claims about objects of inquiry, and principles of epistemic action give directives for further research. If a principle is employed as a guiding principle, then its use integrates both modes of employment: guiding principles imply descriptive claims, and they provide directives for further research. By discussing the correspondence principle and the naturalness principle as examples, I explore the consequences for understanding and evaluating current guiding principles in physics. Like principles of nature, guiding principles are evaluated regarding their descriptive implications about the research object. Like principles of epistemic action, guiding principles are evaluated regarding their ability to respond to context-specific needs of the epistemic agent.

Keywords Guiding principles · Heuristics · Naturalness principle · Correspondence principle

1 Introduction

At the frontiers of contemporary fundamental physics theoretical proposals abound and empirical input is hard to come by. This situation has given rise to a renewed interest in scientific principles. Discussions have put a particular focus on the role of various guiding principles. Examples are the naturalness principle in high-energy physics ('t Hooft, 1980; Giudice, 2008), the (generalized) correspondence principle (Radder, 1991; Bokulich, 2008), a number of principles that are potentially important in the context of developing theories of Quantum Gravity (Crowther & Rickles, 2014; Crowther, 2021) such as the principle of UV-completion (Crowther & Linnemann, 2019) and the Holographic Principle (Bousso, 2002), and Mach's principle, which has

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been of particular interest in the context of developing the general theory of relativity (Norton, 2020).

In this paper I propose an approach to a better understanding of guiding principles in physics. Guiding principles play an important role as heuristic devices for generating new theoretical proposals. I will argue that guiding principles do this by the way they integrate descriptive and prescriptive aspects. Guiding principles attempt to be descriptive of the research objects that they are concerned with. At the same time, they provide directives for further inquiry. This has consequences for how guiding principles are to be evaluated: their implications regarding the object of inquiry need to have at least some initial plausibility, and they need to facilitate the epistemic agents' context-specific needs in order to advance inquiry.

More specifically, I will suggest a distinction between two modes of employing scientific principles. First, principles can be employed as principles of nature. Roughly speaking, principles of nature are understood as making general descriptive claims about the objects of inquiry. For example, the principle of energy conservation implies certain constraints on the possible states of a system's particles. Second, principles can be employed as principles of epistemic action. These are general directives as to what must be done to reach one's epistemic goals. For example, researchers employ various methodological principles, such as principles requiring the falsifiability of theories or the reproducibility of experiments. Most scientific principles are primarily employed either as a principle of nature or as a principle of epistemic action.

When a scientific principle is employed as a guiding principle, then its use integrates aspects of principles of nature and principles of epistemic action. Guiding principles are understood as principles that are about the object of inquiry, and at the same time they are considered to provide general directives as to what needs to be done to advance one's epistemic goals. Pointing out this dual nature of guiding principles sheds new light on the roles that guiding principles play in current fundamental physics and the conditions that need to be fulfilled for such principles to be successful. Like principles of nature, guiding principles are evaluated regarding their descriptive implications about the research object. Like principles of epistemic action, guiding principles are evaluated regarding their ability to respond to context-specific needs of the epistemic agent.

For example, the naturalness principle in high-energy physics is sometimes thought to imply that physics at different energy scales is largely autonomous. At the same time, the principle is often thought to recommend constraints on the degree of fine-tuning exhibited by the parameters of a theory. I will argue that the autonomy-of-scales notion of naturalness is most easily understood along the lines of a potential principle of nature, while the prohibition against fine tuning is better understood as a principle of epistemic action. Distinguishing these roles helps understand why definitions of naturalness take a variety of forms and helps make sense of the different kinds of criticism that the principle has faced.

Given the important role that guiding principles play in contemporary fundamental physics, concrete criteria for evaluating such principles appear desirable. Such specific criteria will have to be determined on a case-by-case basis. But according to my account, overall conditions that do and should play a role in evaluating such principles can be identified. And the main point is that these involve conditions encountered in the context of both principles of nature and principles of epistemic action.

Two remarks about the scope of the discussion are in order. First, the focus of the discussion is the role of guiding principles in theoretical physics. Yet the discussion will also have consequences for experimental and observational physics. For example, the naturalness principle discussed here had also important consequences for motivating high-energy physics experiments (Fischer, 2024b). Second, it should be noted that the concept of guiding principle is sometimes employed in a wider sense that also includes methodological principles. Here the discussion focuses on guiding principles as integrating aspects of principles of nature and principles of action because this is a particularly fruitful approach to understanding guiding principles, as the examples illustrate.[1]

The paper is structured as follows. In Section 2 I will introduce two examples of guiding principles: the correspondence principle and the naturalness principle. At first sight it is these principles' shortcomings that seem particularly striking. In Section 3 I will zoom in on the heuristic role that such principles play and raise the question of what makes a good guiding principle. In Section 4 I will distinguish two functions that scientific principles (in general) can fulfil: they can be employed as principles of nature and as principles of action. In Section 5, I will argue that good guiding principles are those that successfully integrate aspects of principles of nature and principles of action, and I will substantiate these claims by going back to the initial examples of the correspondence principle and the naturalness principle.

2 Guiding principles: two examples

The correspondence principle (CP) is an important guiding principle that has its origin in the context of the development of quantum mechanics, specifically in the work of Niels Bohr. The most widely spread understanding of the principle is that it requires that quantum mechanical systems exhibit classical mechanical behavior in the limit of large quantum numbers. But one can distinguish various meanings of the CP (Radder, 1991; Hartmann, 2002; Bokulich, 2008; Rynasiewicz, 2015). For example, *numerical* correspondence means that quantum mechanics and classical mechanics agree on the numerical values of certain quantities, such as the frequency of the radiation emitted by a hydrogen atom. This numerical correspondence was recognized, according to Radder (1991), before a *conceptual* correspondence between Bohr's atomic model and classical mechanics and electrodynamics had been established.

The CP of quantum mechanics has to be distinguished from the *generalized* correspondence principle (GCP), which applies to inter-theory relations more generally. The GCP can be understood in two ways. First, it can be understood as a *constraint* on new theories stating that any new theory T' should recover the older theory T in the limiting case where the older theory T is known to be successful. Second, it can be understood as a prescription that helps *generating* a new theory out of an old theory by

[1] Employing a distinction common in value theory one may think of the guiding principles discussed here as "substantive guiding principles" and distinguish them from "procedural guiding principles". Thanks to an anonymous reviewer for suggesting this terminology.

"mapping" the older theory on the new theory (Linnemann, 2022, 217). Historically, the relation between quantum mechanics and classical mechanics is the main field of application. But applications can be found across physics and beyond (see French & Kamminga, 1993 for a variety of case studies). It is also the GCP that has inspired an extensive discussion regarding the availability of general heuristic strategies for theory development among philosophers of science and remains controversial (see e.g. Post, 1971). More recently, the GCP has attracted a renewed interest in the context of developing theories of Quantum Gravity, requiring that such theories recover General Relativity in the classical limit (Crowther, 2018, 2021).

The second principle that will be discussed in detail here is the naturalness principle. The naturalness principle has been employed as a guiding principle in high-energy physics and has been particularly relevant in the context of developing new theories beyond the Standard Model of particle physics (BSM). For example, Gerard 't Hooft, states in his key publication introducing the concept of naturalness that it is his "aim to use naturalness as a new guideline to construct models of elementary particles" ('t Hooft, 1980, 137). More recently, Gian Francesco Giudice has discussed the idea of naturalness in a number of programmatic articles, arguing that the "role of naturalness in the sense of 'aesthetic beauty' is a powerful guiding principle for physicists as they try to construct new theories" (Giudice, 2008, 155).

The exact definition of the naturalness principle has been discussed by physicists and philosophers of physics.[2] Here we are concerned with naturalness in the context of the Standard Model Higgs boson. To explain the mass of the Higgs boson, one has to assume that independent parameters of the Standard Model cancel out each other almost exactly. This is not a theoretical inconsistency, yet many physicists have thought that such delicate cancellations require an explanation. They have argued that they represent a violation of naturalness: the idea that independent parameters of a theory should not be finely tuned.

Delicate cancellations could be avoided if new physics would be found in the energy regime just above the Higgs mass, such as predicted by technicolor models (Weinberg, 1976; Susskind, 1979), low energy supersymmetry (Wess & Zumino, 1974; Veltman, 1981), and theories involving extra spatial dimensions (Arkani-Hamed et al., 1998; Randall & Sundrum, 1999). This is why the naturalness principle has inspired and guided many theoretical proposals along these lines (Fischer, 2024a). However, the naturalness principle has come under pressure recently, because no conclusive signs of such new physics could be found in experiments at the Large Hadron Collider (LHC).

What distinguishes these two examples of guiding principles from other kinds of scientific principles, such as the relativity principle or the principle of energy conservation? There are three features that seem to be particularly striking. First, both

[2] According to Susskind, "the naturalness principle requires the physical properties of the output at low energy to be stable against very small variations of [the dimensionless bare couplings and masses]" (1979, 2619). According to 't Hooft, the concept is related to the concept of symmetry: a "physical parameter or set of parameters $\alpha_i(\mu)$ is allowed to be very small only if the replacement $\alpha_i(\mu) = 0$ would increase the symmetry of the system" (1980, 136). For detailed philosophical explanations of these and other concepts of naturalness and the relation between them see Williams (2015, 2019), Wallace (2019), Rosaler (2022), and Fischer (2024a). These discussions are prima facie independent of metaphysical concepts of naturalness or natural properties (Lewis, 1983; Dorr, 2024).

guiding principles are formulated with a considerable amount of leeway and there are multiple versions of the respective principles. As pointed out above, the correspondence principle has been understood in a variety of senses. The variety is particularly wide in the case of the GCP. For example, Hartmann (2002) distinguishes no less than seven kinds of correspondence. Moreover, for any one sense of correspondence there arise questions as to how strict the correspondence has to be in order for the principle to be fulfilled. For example, the special theory of relativity is widely thought to come down to classical mechanics in the limiting case of low velocities. But the relativistic energy-mass equivalence $E = m_0c^2$ does not change in the limit: there is no corresponding equation in classical mechanics (Radder, 1991).

Likewise, the naturalness principle has been understood in a variety of senses. Some relate naturalness primarily to the idea that physics at different energy scales should be largely independent or autonomous (Williams, 2015). Others employ the naturalness principle primarily as a prohibition against fine-tuning (Grinbaum, 2012). While there are strong conceptual links between the various concepts of naturalness, there are also important differences (see Williams, 2015, 2019; Rosaler, 2022 for detailed discussions). Moreover, for any one way to define naturalness there arise questions about what exactly a theory should fulfil to count as natural. For example, there have been various proposals as to how much fine-tuning a theory may display in order to still count as natural (Wells, 2021).

Second, both guiding principles have a weak evidentiary status. While the correspondence principle as a historical principle in the context of relating classical and quantum mechanical theorizing is largely settled now, its ex ante evidential status was not at all clear. In particular, there arose questions regarding the scope of its applicability. This, of course, is related to the foregoing point that various interpretations of the principle are available. But there arise also more specific questions. For example, assuming a conceptual correspondence, would that have to apply to all quantum mechanical concepts? In Section 5 we will see that such questions arose, for instance, with regard to the spin property of electrons.

Similar concerns arise in the context of the naturalness principle. Evidential support for the naturalness principle comes from the observation that the principle is realized in many instances, and that naturalness did help or at least could have helped predicting new phenomena in other places (Wallace, 2019; Bain, 2019). Underlying this is an inductive argument to the effect that one should also expect naturalness in places where it is not known to hold. However, the evidential status of the naturalness principle has come under attack from multiple sides. First, based on the naturalness principle, many physicists expected to discover new physics in current high-energy experiments, but no conclusive signs of new physics have been found to date. This raises doubts regarding the various proposed theories but also regarding the naturalness principle which has been central in motivating these proposals. Moreover, there appear to be other instances in which naturalness does not seem to be fulfilled, as in the case of the cosmological constant problem (Weinberg, 1989) and strong *CP* violation in Quantum Chromodynamics (Dine, 2015).

A consequence of this second point is that guiding principles may advance inquiry, but in that process the guiding principles can be subject to change. They may feature in the final theory only in an altered or revised form or may be overturned altogether.

Pointing to Mach's principle, Crowther (2021), for example, states that a guiding principle "may or may not actually be retained in the resulting theory." Likewise, Norton (2020) argues that Einstein's use of the principle of equivalence can be described in this way. Norton argues that "[i]t did guide Einstein's thinking. However, the principle was defeasible [...] it was diluted in 1912 and all but discarded in 1913 [...]" (18).

So, guiding principles appear to differ from other kinds of scientific principles in that they have multiple and vague formulations, and they have a weak evidential status. A third (and related) aspect is that the motivation or appraisal of guiding principles derives sometimes not so much from theories that are already well-established. Instead, the appraisal is derived, at least partially, from theories that have a promising yet unconfirmed status. This is particularly evident in the example of the naturalness principle, which was considered relevant or even justified because of its special relation to potential future theories of BSM physics (Fischer, 2023).

3 What is a good guiding principle?

The foregoing examples of guiding principles lack a unique and clear formulation, they lack evidential support, and they are sometimes at least partially motivated by theories that lack confirmation. On the one hand, this may explain why such guiding principles are sometimes met with suspicion. On the other hand, science often builds on preliminary ideas in order to proceed or even get started.[3] Thus, even if a principle is imprecise and lacks support, it may still be an important ingredient for developing future ideas, and undue criticism at an early stage could prevent such advancement. In this context, labeling a principle with the mentioned shortcomings as a 'mere' guiding principle can have an important function. By choosing this label, scientists acknowledge the preliminary status of such principles. This may help to protect such principles against undue criticism.

Acknowledgment of the preliminary status of a principle can take various forms. For instance, Currie (2023) observes that sometimes scientists describe their own research as speculative. Scientists do not do this, according to Currie, to discredit their own work but to defend their work based on its potential productivity. Regarding the naturalness principle this strategy has been followed, for example, by 't Hooft. In his 1980 paper on naturalness, he describes the naturalness principle as a "philosophy" (136).

So, the negative features pointed out in the foregoing section are important aspects of the heuristic character of guiding principles. However, they do not explain how guiding principles help generate new ideas. Consider naturalness. One problem with this principle is that it is notoriously difficult to provide an authoritative formulation of the principle. Barbieri and Giudice (1988), for instance, suggest a measure for naturalness that reflects the sensitivity of an output parameter at the electroweak scale (e.g. the physical Higgs mass) to changes of an input parameter at a higher energy scale. According to Barbieri and Giudice, naturalness is violated if this measure exceeds the

[3] See Chang's (2004, 2007) work on the concept of epistemic iteration for the importance of such preliminary ideas and methods.

value 10. This threshold value is related to Dirac's (1938) historical Large Number Hypothesis[4], which states that a theory should not involve dimensionless parameters that are not of the order 1. While a naturalness principle based on such considerations may act as a heuristic device for further research, arguably, a more precise and better justified principle could provide better guidance. This is why many physicists have tried to improve Barbieri and Giudice's initial suggestion.

More generally, it seems that sometimes physicists employ principles that are not well-established and that it is possible to make progress on such grounds. Such preliminary principles are then flagged as guiding principles to indicate the pursuitworthiness of research that is based on them. But the preliminary status is not an indication of the quality of the guiding principle. Instead, one should expect that guidance becomes more reliable if the guiding principle is less vague, has an unambiguous and agreed-upon formulation, and is backed up by well-established theories.[5]

So, what is a good guiding principle? In what follows I will address this question by looking at various roles that scientific principles may play in the context of inquiry. I will distinguish between principles that act as principles of nature (whose main purpose is describing the research object) and principles of epistemic action (whose main purpose is providing directives for inquiry). Guiding principles, I will argue, integrate aspects of both modes of employment. They guide inquiry by giving directives for theory building and such guidance is derived from specific assumptions about the nature of the research object.

4 Principles of nature and principles of action

Before addressing guiding principles, it will be useful to think about scientific principles in general terms. This is a difficult task because the term 'principle' is notoriously ambiguous. For example, both the special relativity principle and the naturalness principle are referred to as 'principles'. However, they seem to be so different that one might question whether they belong to the same category of scientific statements.

Here we will classify principles according to the roles that they can play in scientific inquiry. We shall distinguish two kinds of roles that principles can fulfil. First, a principle may act as a *principle of nature*. If a principle takes this role, then it is assumed to help us describe, understand, predict, and control the behavior of a system. In this sense assumed principles of nature are similar to assumed laws of nature. Unlike laws of nature or even specific equations of motion, principles do rarely provide sufficient resources for predicting a system's dynamics. Instead, they often describe

[4] More precisely, Dirac formulates the Large Number Hypothesis as the requirement that "[*a*]*ny two of the very large dimensionless numbers occurring in Nature are connected by a simple mathematical relation, in which the coefficients are of the order of magnitude unity*" (Dirac, 1938, 201, emphasis original). This was a highly speculative requirement derived from the observation that the ratio of the electric and gravitational force approximates the ratio of the age of the universe and the time it takes light to pass a classical electron. See Kragh (2011, Ch. 4) for further discussion of the historical background of the hypothesis.

[5] Can one imagine circumstances under which a vague and open formulation of a principle can be a benefit? Maybe a vague formulation is beneficial to the recognition of a principle: vagueness may allow agreement on a principle even if researchers disagree on the details. But whether such agreement on a vaguely defined principle advances inquiry is a separate question.

certain constraints on systems. The principle of energy conservation, for example, imposes constraints on the energy states that a system can be in. Likewise, the principle of uncertainty in quantum mechanics imposes constraints on pairs of canonically conjugate variables, such as a particle's position and momentum.

Principles of nature are sometimes described as imposing second-order constraints. Lange (2007), for instance, argues for a distinction between laws and meta-laws. Lange argues that first-order laws of nature necessitate the dynamics of a physical system and therefore can be invoked to explain the dynamics. He argues that meta-laws like symmetry principles analogously necessitate first-order laws of nature. This is the case, according to Lange, because they possess a "stronger variety of natural necessity" (Lange, 2007, 32) than first-order laws.

Scientific practitioners, however, do not seem to limit the use of the concept of principle to statements with such supposed stronger necessity. While examples like the principle of energy conservation and relativistic principles may fit this description, this is less clear for other statements such as Pauli exclusion that are also commonly referred to as 'principles'.

Here we are concerned with 'principles of nature' as a mode of employing scientific statements. Therefore, for our purposes a more adequate way of delineating principles of nature from laws of nature refers to this as a distinction between different ways of using scientific statements. While principles of nature are typically used to impose certain general constraints on physical systems, laws of nature are typically more closely associated with making specific predictions about a system's dynamic. Once accepted, a principle may impose constraints that exclude certain laws. But it may well be the case that certain empirical findings will result in overturning assumed constraints and corresponding principles of nature.

Supposed principles of nature abound in physics. Examples include the relativity principles (Galilean, Einsteinian), Archimedes' principle, Bernoulli's principle, Huygen's principle, the cosmological principle, and causality and locality principles. Beyond physics, supposed principles of nature include the Hardy-Weinberg principle in biology (Luchetti, 2021) and the principle of rationality in economics (Herfeld, 2021). What these (supposed) principles have in common is that they primarily concern the nature of the object of inquiry. The object of inquiry may be anything that is at the focus of research efforts. In physics objects of inquiry include, for example, kinds of fundamental particles, the dynamics of a physical system, or models and idealizations thereof.

An important standard of evaluation for principles, if employed as principles of nature, is that they provide a robust basis for faithful representations of a system's behavior. That is, if the predictions that are being made based on a principle are too unreliable or too far away from what's really going on in the system of interest, then the principle needs to be revised or its domain limited. The principles of Newtonian Mechanics, for example, are the basis of such faithful representations at certain length and energy scales but are known to break down where relativistic effects become relevant.

Principles of nature are rarely employed or evaluated in isolation. Einstein's special theory of relativity, for example, arises from the combination of the relativity principle and the light principle (stating the constancy of the velocity of light in the vacuum).

While each of the principles is well-confirmed, and compatible with classical conceptions of space and time if taken in isolation, it is the reconciliation of the two principles that requires the kinematics of the special theory of relativity.[6]

Second, a principle may be employed as a *principle of action*. A principle of action is a general directive regarding what needs to be done to reach one's goals. Examples for principles of action can be found in all contexts of agency and decision. Ethical principles, for example, are principles that govern an agent's actions that are not only or not exclusively in that agent's own self-interest, but also affect other individuals' interests. In what follows, we will look more specifically at principles of epistemic actions (henceforth epistemic principles), that is, actions that are directed at improving or producing knowledge (Chang, 2022). Such epistemic actions include but are not limited to developing theories, building models, designing and conducting experiments, collecting, processing, and curating empirical data.

Principles of epistemic action inform the inquirer about what she needs to do to reach her goal of contributing to producing or improving knowledge. There is a wide variety of principles that apply to epistemic activity in physics, or science more generally. Most prominently, there are various methodological principles. For example, there are principles that require that scientific theorizing be oriented towards empirical evidence. More specifically, one can base one's theory building on a Popperian principle of falsifiability (Popper, 1959), requiring that the resulting theories be experimentally falsifiable. Other examples are principles of simplicity or parsimony such as Ockham's razor that recommend looking for theories that are as simple as possible or pragmatic principles such as Wheeler's "First Moral Principle: Never make a calculation until you know the answer" (Taylor & Wheeler, 1960, 20).

The standard of evaluation for principles of action is that they work: the agent advances her goals while the principle is being employed. While the primary goal of epistemic actions is contributing to the production and improvement of knowledge, such epistemic goals may not always neatly be separated from other non-epistemic goals. For example, knowing a new fact may count as true progress only if that fact is deemed relevant (Kitcher, 2012). And questions of relevance may depend on epistemic considerations (e.g. does the fact enable us to develop and assess new theories?) and non-epistemic considerations (e.g. does the fact enable us to improve human life?).

Here we will be concerned with epistemic principles that primarily concern the activity of theory building. There are various requirements for such principles to be successfully employed. First, the suggestions and constraints that such principles make need to be sufficiently clear. For example, a principle of testability needs to be based on an idea of what testability amounts to. Moreover, a principle may fail because it excludes kinds of theories and models that would advance the epistemic agent's understanding of the research object. For example, a principle that enforces an overly narrow focus on pursuing theories that can be tested by current experimental means may impose undue limitations. This has been a point of debate in the context of string theory. While some have criticized string theory for the absence of testable predictions and even have questioned its scientific status, others have argued that string theory is

[6] The relevance of combining various principles has also been discussed in the context of Quantum Gravity (Linnemann, 2020).

accompanied by a methodological shift towards non-empirical methods of theory assessment (Dawid, 2013).

On the other hand, epistemic principles may be too permissive in the sense of failing to impose significant constraints on inquiry, and thus will not guard against waste of research efforts. The requirement of testability alone, for example, seems to be too permissive as a principle for theory development in current high-energy physics. This point is illustrated by Hossenfelder (2022), who criticizes current practices in particle physics of suggesting ever new hypotheses regarding the existence of novel particles which are testable, but which have limited initial plausibility. So, testability alone, according to Hossenfelder, is not a sufficient criterion for the pursuitworthiness of a scientific theory. The constraints this criterion imposes on the space of possible theories are too weak.

This last point also illustrates that, like principles of nature, principles of action rarely act in isolation. First, principles of epistemic action will typically be in some way related to epistemic virtues. The principle to look for testable theories, for example, will be related to considerations regarding empirical adequacy. Other important factors are the individual researcher's abilities and motivations, the research community's preferences and capabilities, as well as the material context including resources, facilities, and methods available to the research community. A principle of epistemic action will have a meaningful impact on a researcher's agenda only if it stands in a relation of coherence with these aspects influencing a researcher's epistemic activity.

One consequence of this is that the usefulness of principles of epistemic action depends on the context and has a temporal dimension. A principle may lose its usefulness as an epistemic principle and may be replaced by other principles if the suggestions that it makes and constraints that it imposes are no longer significant. Testability, for example, is a relevant epistemic principle if there are only few testable theories in the pool of possible theories. If it turns out that many testable theories can be developed, then interest in a testability principle will diminish and further methodological criteria will be looked for. The value of a principle of epistemic action depends on the epistemic state of the agent or research community and on the research context.

So far, I have argued for a distinction between two modes of employing scientific principles: as principles of nature or as principles of action. Here is a potential worry. One might argue that the distinction collapses because there are strong connections between the two modes of employment. First, it seems that supposed principles of nature sometimes act as principles of epistemic action, that is, as principles that inform scientists about how to develop specific theories and laws of nature, especially because principles of nature themselves are often not directly predictive. For example, Newton's first law, on its own, does not make predictions about the behavior of particles, it is instead a general directive for developing equations of motion that take the state of uniform non-accelerated motion as default state. But if Newton's first law acts as such a general directive for developing specific models, how does it differ from other principles such as the falsifiability principle which I have characterized as a principle of action above?

I agree that a strict separation between the two roles that scientific principles can play is certainly not viable in all cases. In fact, I will argue that guiding principles are an important class of scientific principles that can be understood as integrating both functions. Yet, there is a distinction to be made between the two modes of employing a scientific principle. If a principle is employed as a principle of nature, then it is primarily taken to be concerned with the nature of the object of inquiry. It will be concerned, for example, with a point particle's default state of motion (Newton's first law) or the velocity and momentum of a quantum object (uncertainty principle). The claims that are inferred from the principle about the object of inquiry can turn out to be true or false. Principles of action, by contrast are primarily concerned with epistemic actions. They inform researchers about what to do with theories and models. The resulting theories and models can be more or less faithful representations. Yet the principle's recommendations have a prescriptive nature which is to be evaluated with regard to questions of usefulness.

A related worry is that if a principle of action is to be successful (in the sense of improving knowledge), then it will have to correspond in some way or another to true claims about nature. Directives for epistemic action that are detached from claims about the system under consideration are unlikely to advance inquiry.

However, unlike principles of nature, principles of epistemic action primarily concern *how* researchers attain that knowledge and take into account the pragmatic and potentially contingent factors of the context of inquiry. They take into account, for example, that researchers will operate most effectively with theories and models that follow ideals of simplicity, or they acknowledge that researchers may commit errors, when they recommend the kind of double checking suggested by Wheeler's First Moral Principle.

5 Guiding principles

Guiding principles like the correspondence principle and the naturalness principle, I propose, integrate aspects of principles of nature and principles of epistemic action. Guiding principles are associated with claims that are supposed to be descriptive regarding the object of inquiry. At the same time, they can be understood as involving explicit prescriptions as to what criteria a theory should fulfil. Along both lines, guiding principles can help suggest new theories and impose constraints, but neither do they entirely determine the nature of the object of inquiry, nor do they determine the steps that need to be taken to develop a theory or model.

The descriptive aspect can be understood as the source of guidance. A guiding principle will direct research in a certain direction because it is based on assumptions about the nature of the object of inquiry. This is how guiding principles (in the sense here suggested) differ from 'mere' principles of epistemic action, such as methodological principles. Methodological principles provide guidance, but they typically do so in a general way, without an eye to the specific nature of the object of inquiry. The prescriptive aspect can be understood as the actual guidance provided by the principle, that is, the suggestions for generating new theories and the constraints imposed on them. This is how guiding principles differ from principles of nature, which imply claims about the object of inquiry but are not primarily employed to give directions for further theory development.

This has consequences for the conditions of success of guiding principles. First, good guiding principles need to have at least an initial plausibility regarding their underlying assumptions about the nature of the object of inquiry. Otherwise, they may guide research in a wrong direction. Here quality comes in degrees. The more descriptively adequate the principle is, the more reliable will the guidance be that the principle can provide. Ideally, one's research is based on perfectly reliable guiding principles. But in most cases researchers must cope with less than the ideal.

The condition of initial plausibility is relevant for distinguishing guiding principles from mere principles of epistemic action such as methodological principles. A guiding principle, according to the understanding suggested here, may be attacked on the grounds that it is not descriptively adequate, that it gets something wrong about the specific nature of the object of inquiry. A methodological principle, by contrast, does not involve such descriptive claims, and thus cannot be challenged in this way. If anything, one can challenge the applicability or usefulness of a methodological principle in a certain research context.

Second, guiding principles are any good only if they help an agent advance her epistemic goals. As we will see from the discussion of the examples, there are two ways guiding principles can achieve this. First, guiding principles can make suggestions for generating new theories. Second, guiding principles can impose constraints on theories. In both cases guiding principles can fail in various ways. For example, the principle's suggestions for theory generation are only helpful if they are not overly ambiguous (see Linnemann, 2022 for a discussion of ambiguities associated with quantization). Moreover, if the constraints imposed by a principle are too strict, the principle will disallow decisions that would be conducive to the goal. If the constraints are too loose, then the guiding principle will allow too many options that are not conducive to the goal. As in the case of principles of action the usefulness of principles of guiding principles depends on the research context and has a temporal dimension.

In this sense, the evaluation criteria for guiding principles are more demanding than the evaluation criteria for principles that are employed as principles of nature. If it is descriptively adequate, a principle like Archimedes' principle will remain a good principle of nature, irrespective of potential changes to the researcher's epistemic state. A principle is a good guiding principle only if it stands in the right relation to the epistemic needs of the researcher.

Let's cash out the idea of the dual character of guiding principles by looking more closely at the correspondence principle and the naturalness principle. More specifically, suppose that the correspondence principle and the naturalness principle are guiding principles. Suppose also that guiding principles integrate aspects of principles of nature and principles of action as suggested here. Then this has consequences for how these principles should be evaluated. In what follows, I will argue that this is reflected by the kinds of discussions that these principles face.

5.1 Correspondence

Consider the correspondence between quantum mechanical and classical quantities (CP). There is a discussion of what exactly is to be learned from this correspondence, whether, for example, it has "predictive muscle", or not (Rynasiewicz, 2015). But certainly, it can play a heuristic role in two ways. First, it can help establish a potentially acceptable theory of quantum mechanics, for instance, by way of Born's quantization rule (see Radder, 1991, 216). Second, it can be seen as imposing post-hoc constraints on quantum mechanics.

The general correspondence principle (GCP) fulfils its heuristic function in a similar way. First, it can help establish a potentially acceptable new theory in the first place. Second, it can act as a post-hoc constraint. Post expresses this second aspect as follows: "We shall consign to the wastepaper basket any L-theory [i.e. new theory], the brainchild of a careless night, when we realize in the morning that this candidate does not fulfil the general correspondence principle, does not explain why the previous S-theory [i.e. old theory] worked" (Post, 1971, 235). Usually, the GCP is not sufficient to make a unique suggestion for the new theory or to impose constraints that uniquely determine the new theory. As indicated in the discussion above, the usefulness of the principle will depend upon whether there are other principles that the (G)CP needs to be combined with, and on the broader context of inquiry.

The characterization of correspondence principles so far would be consistent with them being principles of epistemic action. Yet, correspondence principles also involve descriptive claims about the object of inquiry. The CP involves claims about the relation between classical theories and quantum mechanics that can turn out to be true or false. What these claims are depends, of course, on the specific reading of the correspondence principle. The descriptive content of the CP may be particularly clearly visible in Bokulich's (2008) interpretation, according to which Bohr considered the CP to be a law of quantum mechanics. Understood in this sense, Bokulich argues, the correspondence principle amounts to the selection rule, a principle that restricts the allowed quantum transitions not just for high but for all quantum numbers.

While the preceding paragraph concerns numerical correspondence, there is also descriptive content to the conceptual correspondence between classical theories and quantum mechanics. There arise questions as to whether it is true that all quantum mechanical concepts stand in a relation of correspondence to concepts in classical theories. That this is a relevant question is illustrated by historical discussions about the electron spin between Bohr and Pauli (Massimi, 2005). Initially, Bohr was quite skeptical whether Pauli's suggestion of the electron spin was not "complete madness", because it would amount to declaring "the definitive death sentence" regarding correspondence-like explanations (Bohr to Pauli, 22 December 1924, Pauli, 1979, 194). But Pauli's idea of the electron spin prevailed, meaning that a conceptual continuity between classical theories and Quantum Mechanics is not manifest in this context.

The GCP does not concern a specific theory and, thus, it is not concerned with a specific object of inquiry. So, the descriptive consequences of the GCP may be harder to identify. But its applicability still depends, of course, on a general descriptive assumption of the continuity of nature—a continuity that allows describing the world with the help of theories that stand in the kind of relation described by the GCP. If we lived in a Cartwrightian "dappled world" (Cartwright, 1999) the heuristic value of the GCP, presumably, would be quite limited.

5.2 Naturalness

The status of naturalness as a guiding principle is much more contested than the status of the correspondence principle. But as in the case of correspondence, I argue, the character of the principle as a guiding principle is reflected by the kinds of support that the naturalness principle is thought to receive and the kinds of challenges it faces.

The naturalness principle has been given various formulations. Most prominently, naturalness has been understood as being related to the autonomy of physics at widely separated energy scales, on the one hand, and as a prohibition against fine-tuning of parameters, on the other hand. Both conceptions are linked to each other. In many cases autonomy is understood as the absence of a sensitive dependence of low-energy physics on high-energy physics, a kind of dependence that can be quantified by fine-tuning measures. But there are also slight differences.

Naturalness as related to assumptions about the autonomy of scales makes a descriptive claim about physics at different scales. Such claims about the autonomy of scales are often supported inductively. A common strategy for justifying the naturalness principle is pointing to various instances in which physics turned out to be natural, as in the examples of the charm quark, the positron, and the ρ-meson (Bain, 2019). Relatedly, Wallace (2019) takes up the idea that the naturalness principle plays an important role for the relation of physics at different scales. He argues that "naturalness assumptions are the glue that links physical explanations at different levels: if we simply reject their legitimacy then we undermine almost everything we know about inter-theoretic reduction in physics"—and rejecting the naturalness principle, according to Wallace, is an empirical question, not a methodological (2019, 511f). Relatedly, proponents of naturalness as associated to the relation between physics at different scales see the largest threats coming from apparent empirical violations. The most prominent empirical threat to the naturalness principle arises in the context of the Higgs boson, because despite high expectations no new physics has been found at the LHC.

Naturalness as a prohibition against fine-tuning seems to be better understood in the sense of a principle of action. Naturalness in this sense helps make concrete recommendations for theory-building by imposing constraints on the permissible amount of fine-tuning. That naturalness in this sense is more easily understood as a principle of action is also reflected by the kind of criticisms that have been put forward against the principle. Criticism against fine-tuning measures has been voiced particularly strongly since physicists' expectations to discover new physics at the LHC have been disappointed. Yet the actual points of criticism that have been put forward since then are largely independent of the absence of new findings and focus on theoretical issues that could have been voiced just as well before the empirical threats became acute.

Taking up ideas by Wetterich (1984), Rosaler and Harlander (Rosaler & Harlander, 2019; Harlander & Rosaler, 2019; Rosaler, 2022), for example, argue that "the need for fine tuning of the renormalized Higgs mass parameter is an eliminable, unphysical artifact of renormalization scheme, and that this severely weakens the grounds for regarding it as a problematic instance of fine tuning" (Harlander & Rosaler, 2019, 879). This criticism is not targeted at a supposed principle of nature that would prohibit fine-tuning. Instead, the criticism is to be understood as a warning against taking certain fine-tunings that feature in our theories too seriously: it may be a bad strategy to take such fine-tunings as indicators for new physics if such fine-tunings are just an unphysical artifact.

Another point of criticism against common measures of fine-tuning addresses the theoretical assumptions going into such measures. Hossenfelder (2018) addresses probabilistic measures of fine-tuning. Such measures are based on assumptions regarding probability distributions over parameter space. Hossenfelder objects that such assumptions (typically proposing an almost uniform probability distribution) introduce an element of arbitrariness and threaten to make the technical machinery of probabilistic naturalness concepts redundant. Again, this criticism is primarily a warning against taking occurrences of supposed fine-tuning too seriously, in this case, because they might simply be a result of arbitrary choices of probability distributions. This argument, thus, is not so much concerned with physics being natural or not. It rather seems to be concerned with whether measures of fine-tuning would track such a property (and then there may be additional reasons not to base one's evaluations of theory pursuitworthiness on assumptions of naturalness).

My proposal has been to understand guiding principles as integrating aspects of two modes of employment of scientific principles, that of principles of nature and that of principles of epistemic action. These modes of employment of principles are evaluated differently. While principles of nature need to provide grounds for plausible claims about the object of inquiry, principles of action need to make useful recommendations for theory building. Thus, if naturalness is understood as a guiding principle, one should expect that both these ways of evaluating the principle play a role. And this seems to be the case in current discussions about the naturalness principle. The 'autonomy of scales' notion is relevant as a contested assumption about the object of inquiry: physics at different energy scales. But this assumption alone would not be sufficient to provide guidance. The principle needs to be operationalized in a way that imposes significant constraints on theory building. Whether that has been achieved is at stake in discussions about fine-tuning measures.

I have argued that a more comprehensive understanding of the heuristic role of naturalness is available if we describe the naturalness principle as integrating aspects of principles of nature and principles of action. What is the benefit of this approach? First, it sheds new light on the role of the specific formulations of the principle. Focusing on the preliminary status of the naturalness principle, the variety of formulations may simply be identified as a lack of clear formulation. The functional approach proposed here instead explains that the different formulations respond to different roles in the research context: that of naturalness as a principle of nature and that of naturalness as a principle of action.[7]

[7] What is the relation between the principle of naturalness and its more concrete specifications? This can be understood as a question about how physicists have used the principle. Since the naturalness principle has been used in different ways in different contexts of application, its use may resemble that of theoretical values (Kuhn, 1974; McMullin, 1982). The approach provided here can then help explain the variation in the usage: different roles have led to different specifications of the principle. There is another question of how the principle *should* be used. According to the approach that I have developed here, guiding principles may display variation depending on whether they are primarily employed as principles of nature or as principles of action. Yet the guiding principle should be used coherently across these modes of employment.

Such a distinction between the roles of a guiding principle may also help explain why guiding principles lose their guiding role and may indicate why guiding principles should lose that role. If particle physics is entering a "post-naturalness era" (Giudice, 2018) that may be because physicists acknowledge that the naturalness principle is not realized in the Higgs case. But it may also be the case that physicists acknowledge that a natural explanation of the Higgs mass is still available, but that searching for such an explanation is not the most efficient way to generate new insights—meaning that the naturalness principle should be dropped for pragmatic purposes.

Finally, guiding principles sometimes need to be prioritized over other guiding principles. Recognizing that guiding principles can fulfil their roles to varying degrees may help explain why such decisions are being made and should be made in favor of one (set of) guiding principle(s) rather than another. This is relevant in the context of deciding between various formulations of the naturalness principle and specific attempts to operationalize the principle in terms of fine-tuning measures (Grinbaum, 2012). Moreover, this is relevant in contexts where naturalness considerations stand in trade-off relations with other guidelines or values such as simplicity (Dine, 2015). Finally, such comparative evaluation of guiding principles may also be relevant for understanding other kinds of cases. Norton (2020), for example, distinguishes between the equivalence principle as a first-tier heuristic in the development of general relativity which was replaced by conservation principles as a second-tier heuristic.

6 Conclusion

Guiding principles in physics often have multiple and vague formulations, they tend to have a weak evidentiary status, and their motivation is sometimes derived from theories that are considered promising rather than well established. These features are important for understanding the heuristic role that guiding principles play.

But a more comprehensive understanding of the heuristic role is available if guiding principles are understood as integrating aspects of principles of nature and principles of epistemic action. When a principle is employed as a principle of nature, then it is thought to imply descriptive claims about the corresponding object of inquiry. The primary criterion of evaluation in this mode of employment is that such implications are accurate. When a principle is employed as a principle of epistemic action, then it is thought to provide general directives for reaching one's epistemic goals. The primary criterion of evaluation in this mode of employment is the principle's context-specific usefulness.

The dual aspect account has implications for how guiding principles are to be evaluated. Good guiding principles help generate new theories or they provide constraints that are meaningful in context-specific research circumstances and that derive their guiding force from descriptively adequate assumptions about the object of inquiry. I have shown how this can help us understand the use of principles such as the naturalness principle, where the autonomy-of-scales formulation seems to be more easily understood as a principle of nature and the prohibition against fine-tuning as a principle of action.

The paper has focused on correspondence and naturalness as examples of guiding principles. Further guiding principles are Mach's principle and renormalizability. Mach's principle involves descriptive claims about the status of motion of an accelerated body and its relation to other, potentially distant bodies. However, the principle says so little about the relation between the acceleration and other bodies that it can rather be understood as a call for epistemic action. Norton (1995), for example, argues that the principle in this formulation "is not so much a proposal of a definite, new physical law; rather it is the prescription that such a law should be found" (9f).

Renormalization techniques are employed to deal with divergences that arise in quantum field theories (Butterfield & Bouatta, 2016). Renormalizability means that all divergences can be absorbed with a finite number of constants. A *principle* of renormalizability imposes renormalizability as a guideline for acceptable quantum field theories. As a principle of action this constraint is related to considerations of epistemic utility: a theory with an infinite number of constants would require infinite input to be predictive. As a principle of nature renormalizability may be related to assumptions about the autonomy of scales in analogy to naturalness, but in a different way (see Franklin, 2020).

The account also suggests conditions for evaluating future guiding principles. Specific criteria for such evaluations will, arguably, have to be studied on a case-by-case basis. Yet the main lesson to be learnt from my account is that any catalogue of evaluation criteria for guiding principles will have to consider the principle-of-nature aspect (descriptive adequacy; as indicated, for instance, through agreement with empirical constraints, previous successful cases, coherence with extant theories) and the principle-of-action aspect (meeting the researcher's context-specific constraints, such as limitations on the kinds of experiments available).

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References

Arkani-Hamed, N., Dimopoulos, S., & Dvali, G. (1998). The hierarchy problem and new dimensions at a millimeter. *Physics Letters B, 429*(3), 263–272.

Bain, J. (2019). Why be natural? *Foundations of Physics, 49*, 898–914.

Barbieri, R., & Giudice, G. F. (1988). Upper bounds on supersymmetric particle masses. *Nuclear Physics B, 306*, 63–76.

Bokulich, A. (2008). *Reexamining the quantum-classical relation: Beyond reductionism and pluralism*. Cambridge University Press.

Bousso, R. (2002). The holographic principle. *Reviews of Modern Physics, 74*, 825–874.

Butterfield, J., & Bouatta, N. (2016). Renormalization for philosophers. In T. Bigajund & C. Wüthrich (Eds.), *Metaphysics in contemporary physics* (pp. 437–485). Brill.

Cartwright, N. (1999). *The dappled world. A study of the boundaries of science*. Cambridge University Press.

Chang, H. (2022). *Realism for realistic people. A new pragmatist philosophy of science*. Cambridge University Press.

Chang, H. (2004). *Inventing temperature: Measurement and scientific progress*. Oxford University Press.

Chang, H. (2007). Scientific progress: Beyond foundationalism and coherentism. *Royal Institute of Philosophy Supplements, 61*, 1–20.

Crowther, K. (2018). Inter-theory relations in quantum gravity: Correspondence, reduction and emergence. *Studies in History and Philosophy of Modern Physics, 63*, 74–85.

Crowther, K. (2021). Defining a crisis: The roles of principles in the search for a theory of quantum gravity. *Synthese, 198*, 3489–3516.

Crowther, K., & Linnemann, N. (2019). Renormalizability, fundamentality, and a final theory: The role of uv-completion in the search for quantum gravity. *The British Journal for the Philosophy of Science, 70*(2), 377–406.

Crowther, K., & Rickles, D. (2014). Introduction: Principles of quantum gravity. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics, 46*, 135–141.

Currie, A. (2023). Science & speculation. *Erkenntnis, 88*, 597–619.

Dawid, R. (2013). *String theory and the scientific method*. University of Cambridge Press.

Dine, M. (2015). Naturalness under stress. *Annual Review of Nuclear and Particle Science, 65*, 43–62.

Dirac, P. A. M. (1938). A new basis for cosmology. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 165*(921), 199–208.

Dorr, C. (2024). Natural properties. In E. N. Zalta, & U. Nodelman, (Eds.) *The stanford encyclopedia of philosophy*. Metaphysics Research Lab, Stanford University, Summer 2024 edition.

Fischer, E. (2023). Naturalness and the forward-looking jusitification of scientific principles. *Philosophy of Science,* 1–19.

Fischer, E. (2024a). The promise of supersymmetry. *Synthese, 203*(6).

Fischer, E. (2024b). No-lose theorems and the pursuitworthiness of experiments. https://philsci-archive.pitt.edu/23856/

Franklin, A. (2020). Whence the effectiveness of effective field theories? *The British Journal for the Philosophy of Science, 71*(4), 1235–1259.

French, S., & Kamminga, H. (Eds.). (1993). *Correspondence, invariance and heuristics*. Number 148 in Boston Studies in the Philosophy and History of Science. Springer.

Giudice, G. F. (2008). *Perspectives on LHC physics*, chapter Naturally Speaking: The naturalness criterion and physics at the LHC (pp. 155–78). World Scientific.

Giudice, G. F. (2018). The dawn of the post-naturalness era. In *From my vast repertoire*. World Scientific.
Grinbaum, A. (2012). Which fine-tuning arguments are fine. *Foundations of Physics, 42*, 615–631.
Harlander, R., & Rosaler, J. (2019). Higgs naturalness and renormalized parameters. *Foundations of Physics, 49*, 879–897.
Hartmann, S. (2002). On correspondence. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics, 33*(1), 79–94.
Herfeld, C. (2021). Understanding the rationality principle in economics as a functional a priori principle. *Synthese, 198*(Suppl 14), 3329–3358.
Hossenfelder, S. (2022). No one in physics dares say so, but the race to invent new particles is pointless. *The Guardian*.
Hossenfelder, S. (2018). *Lost in math: How beauty leads physics astray*. Basic Books.
Kitcher, P. (2012). *Science in a democratic society*. Prometheus Books.
Kragh, H. (2011). *Higher speculations. Grand theories and failed revolutions in physics and cosmology*. Oxford University Press.
Kuhn, T. S. (1974). Objectivity, value judgement, and theory choice. In *The essential tension: Selected studies in scientific tradition and change*. University of Chicago Press.
Lange, M. (2007). Laws and meta-laws of nature: Conservation laws and symmetries. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics, 38*(3), 457–481.
Lewis, D. (1983). New work for a theory of universals. *Australasian Journal of Philosophy, 61*, 343–77.
Linnemann, N. (2020). Non-empirical robustness arguments in quantum gravity. *Studies in History and Philosophy of Modern Physics, 72*, 70–86.
Linnemann, N. (2022). Quantisation as a method of generation: The nature and prospects of theory changes through quantisation. *Studies in History and Philosophy of Science, 92*, 209–223.
Luchetti, M. (2021). Constitutive elements in science beyond physics: The case of the Hardy-Weinberg principle. *Synthese, 198*(Suppl 14), 3437–3461.
Massimi, M. (2005). *Pauli's exclusion principle. The origin and validation of a scientific principle*. Cambrdige University Press.
McMullin, E. (1982). Values in science. *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association* (pp. 3–28).
Norton, J. D. (1995). Mach's principle before Einstein. In J. Barbour, & H. Pfister, (Eds.), *Mach's principle. From Newton's bucket to quantum gravity* (pp. 9–57). Birkhäuser.
Norton, J. D. (2020). Einstein's conflicting heuristics: The discovery of general relativity. In C. Beisbart, T. Sauer, & C. Wüthrich (Eds.), *Thinking about space and time: 100 years of applying and interpreting general relativity* (pp. 17–48). Birkhäuser.
Pauli, W. (1979). *Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg u.a., Band1: 1919–1929*. Springer.
Popper, K. (1959). *The logic of scientific discovery*. Hutchinson and Co.
Post, H. (1971). Correspondence, invariance and heuristics: In praise of conservative induction. *Studies in History and Philosophy of Science, 2*, 213–255.
Radder, H. (1991). Heuristics and the generalized correspondence principle. *The British Journal for the Philosophy of Science, 42*(2), 195–226.
Randall, L., & Sundrum, R. (1999). Large mass hierarchy from a small extra dimension. *Physical Review Letters, 83*, 3370–3373.
Rosaler, J. (2022). Dogmas of effective field theory: Scheme dependence, fundamental parameters, and the many faces of the higgs naturalness principle. *Foundations of Physics, 52*(2), 1–32.
Rosaler, J., & Harlander, R. (2019). Naturalness, Wilsonian renormalization, and "fundamental parameters" in quantum field theory. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics, 66*, 118–134.
Rynasiewicz, R. (2015). The (?) correspondence principle. In F. Aaserud, & H. Kragh, (Eds.), *One hundred years of the Bohr Atom. Proceedings from a Conference* (pp. 175–99). Det Kongelige Danske Videnskabernes Selskab, Copenhagen.
Susskind, L. (1979). Dynamics of sponatneous symmetry breaking in the Salam-Weinberg theory. *Physical Review D, 20*(10), 2619–2625.
't Hooft, G. (1980). Naturalness, chiral symmetry, and spontaneous chiral symmetry breaking. In *Recent developments in Gauge theories*. Springer.
Taylor, E. F., & Wheeler, J. A. (1960). *Spacetime physics. Introduction to special relativity* (2nd Edn.). W. H. Freeman and Company.

Veltman, M. J. G. (2019). The infrared - ultraviolet connection. *Acta Physica Polonica B, 12*, 437–457.
Wallace, D. (2019). Naturalness and emergence. *The Monist, 102*(4), 499–524.
Weinberg, S. (1976). Implications of dynamical symmetry breaking. *Physical Review D, 13*, 974–996.
Weinberg, S. (1989). The cosmological constant problem. *Reviews of Modern Physics, 61*(1), 1–23.
Wells, J. (2021). Evaluation and utility of Wilsonian naturalness. arXiv:2107.06082
Wess, J., & Zumino, B. (1974). Supergauge transformations in four dimensions. *Nuclear Physics B, 70*(1), 39–50.
Wetterich, C. (1984). Fine-tuning problem and the renormalization group. *Physics Letters B, 140*(3–4), 215–222.
Williams, P. (2015). Naturalness, the autonomy of scales, and the 125 GeV Higgs. *Studies in History and Philosophy of Science Part B: Studies in in History and Philosophy of Modern Physics, 51*, 82–96.
Williams, P. (2019). Two notions of naturalness. *Foundations of Physics, 49*, 1022–1050.