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Naturalness and the Forward-Looking Justification of Scientific Principles

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Abstract

It has been suggested that particle physics has reached the "dawn of the post-naturalness era." I explain the current shift in particle physicists' attitude toward naturalness. I argue that the naturalness principle was perceived to be supported by theories it has inspired. The potential coherence between major beyond the standard model (BSM) proposals and the naturalness principle led to an increasing degree of credibility of the principle among particle physicists. The absence of new physics at the Large Hadron Collider (LHC) has undermined the potential coherence and has led to the principle's loss of significance.

1. Introduction

The naturalness principle roughly demands that a theory should not involve independent parameters that are finely tuned. This principle was employed heavily over the last 40 years by theoretical physicists as a guideline for developing theories of beyond the standard model (BSM) physics. However, because experiments at the Large Hadron Collider (LHC) have not found conclusive signs of new physics, the theories look far less promising today. As a consequence, the significance of naturalness arguments has been questioned, and it has been suggested that high-energy physics has reached the "dawn of the post-naturalness era" (Giudice (2018)).

Among philosophers of science, there is now a vital theoretical debate about the credibility of naturalness as a guiding principle in particle physics. On the one hand, there are authors who argue that assumptions of naturalness are deeply entrenched in physics (Williams (2015); Wallace (2019)). For these contributors, the absence of BSM physics poses a deep challenge to established forms of reasoning in particle physics and beyond. On the other hand, there are authors who are more skeptical about the naturalness principle and its role in current particle physics (Harlander and Rosaler (2019)) and authors who take the absence of new findings as an indication that theory development should not have been influenced so strongly by the naturalness principle (Hossenfelder (2021)).

But either view provides only a partial explanation of the current change in attitude toward naturalness arguments. From the viewpoint of the proponent of naturalness, it appears plausible that the naturalness principle was employed so heavily over the last 40 years. But from this viewpoint, one should also expect that as a result of the non-findings, the relevance of the naturalness problem increases. This seems to be at odds with the current loss of relevance of such arguments in theory development. From the viewpoint of opponents of naturalness, the current loss of significance of naturalness arguments is explained more easily. But from this viewpoint, there arises a question of why naturalness arguments were employed so heavily in the first place.

In this article, I argue that a better explanation of the current shift in the attitude toward naturalness is available if we acknowledge that particle physicists took the naturalness principle to be justified through forward-looking considerations. A forward-looking justification of a principle can derive from coherence with promising ideas that the principle gives rise to. This form of justification differs from more traditional forms of justification that relate a principle to claims that have already been secured. Before the discovery of the Higgs boson, the naturalness principle had given rise to a number of diverse and promising theories of BSM physics. The potential coherence between these theoretical proposals and the naturalness principle led to an increasing degree of credibility of the principle among particle physicists. This has changed since experiments in the relevant energy regime have been conducted. Once the experiments showed no signs of new physics, doubts started to rise in regard to the naturalness principle because the options of coherence between the principle and promising BSM approaches became more and more limited.

In section 2, I introduce the naturalness principle and a few BSM proposals the principle has inspired. In section 3, I characterize the recent change in attitude toward naturalness. In section 4, I raise a challenge for extant approaches to justifications of naturalness that derives from the recent change in attitude. In section 5, I argue that a better explanation of this change is available if we acknowledge that the naturalness principle was taken to be justified in a forward-looking way. In section 6, I consider consequences for our understanding of naturalness as a guiding principle in high-energy physics.

2. Naturalness and the standard model Higgs

A common way of formulating the Higgs naturalness problem (Susskind (1979)) arises in the context of treating the standard model (SM) of particle physics as an effective field theory (EFT). Despite the enormous predictive success of the SM, it is known to fail at arbitrarily high energies because of gravity. The EFT framework takes this into account by describing the SM as a field theory that is predictively accurate below an ultraviolet cutoff, whereas the SM is thought to break down above that cutoff.

In this framework, the squared physical Higgs mass m_p^2 can be written to leading order as the sum of the squared bare Higgs mass $\tilde{m}_0^2$ and quantum corrections that depend on the top Yukawa coupling $y_{t,0}$:

$$m_p^2 = \Lambda_{\mathrm{SM}}^2 \left(\tilde{m}_0^2 - \frac{y_{t,0}^2}{8\pi^2} \right) + \ldots .$$

Experiments at the LHC have confirmed that the physical Higgs mass m_p is at 125 GeV, which leads to a quantity of the order of 10^4 on the left-hand side of the equation. It is typically assumed that the SM is valid up to the Planck scale $\Lambda = 10^{19}$ GeV (where gravitational effects become relevant). This gives a quantity of the order of 10^{38} in front of the brackets. Then the quantity in the brackets has to be of order 10^{-34}. But this means that the bare parameter $\tilde{m}_0^2$ and the contribution from quantum corrections have to coincide over 33 orders of magnitude, then be different. This strikes many physicists to be an odd coincidence.

There are a number of different diagnoses of the naturalness problem, associated with a variety of conceptually interconnected formulations of the naturalness principle. The simplest form of the naturalness consideration is expressed by the idea of *absolute naturalness* going back to Paul Dirac. This is an aesthetic criterion requiring that a theory should only involve dimensionless parameters of order 1. Absolute naturalness is violated because the term in the brackets needs to be of the order of 10^{-34} if we assume that the cutoff is at the Planck scale.

Technical naturalness is a slightly weaker requirement formulated by 't Hooft (1980) and demands that a dimensionless quantity of a theory be much smaller than 1 only if it is "protected" by a symmetry. A parameter is protected by a symmetry if setting the parameter to zero increases the symmetry of the theory. Technical naturalness is taken to be violated by the SM Higgs because setting the quantity in the brackets to zero does not increase the symmetry of the SM.

Naturalness is also sometimes described as a *prohibition against fine-tuning*. The degree of fine-tuning, in turn, can be measured in different ways (Grinbaum (2012)). First, fine-tuning is often understood in the sense of sensitive dependence. In the Higgs case, there is sensitive dependence because slightly changing the bare parameter $\tilde{m}_0^2$ has dramatic consequences for the physical Higgs mass. Second, fine-tuning is sometimes understood in the sense of requiring very special or unlikely parameter choices. Prima facie, it seems unlikely that two unrelated parameters, such as the Higgs bare mass and the quantum corrections, coincide over so many orders of magnitude but then differ at order 10^{-34}.

Finally, naturalness has been described as a requirement for the *separation* or *autonomy of scales* (Giudice (2008); Williams (2015)). Separation of scales means that the physics at low energies does not depend sensitively on the physics of energies that are several orders of magnitudes higher. Separation of scales is supposedly violated in the Higgs case because a slight variation of the bare mass—at the Planck scale—would lead to a vastly different physical Higgs mass, which is located at the electroweak scale.

Note that there are important conceptual connections between the different formulations. For example, the autonomy-of-scales formulation of naturalness employs a notion of sensitive dependence. But the notions of naturalness can also come apart. Assuming a nonuniform probability distribution over the parameter space, for example, fine-tuning in the sense of sensitive dependence does not imply fine-tuning in the sense of unlikely parameter choices (Williams (2019)). In what follows, the details will not matter. It does matter, though, that there are various formulations and that these formulations are often employed interchangeably by particle physicists.

The naturalness problem associated with the SM Higgs boson would be solved if the cutoff parameter Λ_{SM} were much smaller. This would indicate that the SM is not valid up to the Planck scale and that new physics arises closer to the scale of electroweak breaking. This is why the naturalness principle has inspired a wide range of models of BSM physics. In order to illustrate the variety of suggestions, let us have a quick look at the following examples.

A common diagnosis is that the naturalness problem of the SM arises because the Higgs boson is assumed to be an elementary scalar boson, the only known boson of this kind. *Technicolor* models (Weinberg (1976); Susskind (1979)), historically the first models developed in response to the naturalness problem, try to avoid introducing such an elementary scalar by dynamically generating W and Z masses. However, problems for technicolor were known before the discovery of the Higgs boson, and technicolor models have been particularly under pressure since the Higgs boson was found to be much lighter than 1 TeV and to have a width of less than a few giga-electron volts (Dine (2015)).

Supersymmetry (SUSY) posits a symmetry between integral and half-integral spins and implies that there are new boson partners for all known fermions, and vice versa. As a result, the masses of elementary scalar fields would be protected by symmetries, just as required by 't Hooft's technical notion of naturalness. Unlike research on technicolor models, research on SUSY was initiated independently of naturalness arguments. In 1974, the first supersymmetric theory in four dimensions was developed by Wess and Zumino (1974), and the idea that SUSY might satisfy the naturalness principle was proposed only in the early 1980s (e.g., Veltman (1981)). The simplest implementation of SUSY is the minimal supersymmetric standard model (MSSM). But for the MSSM, a Higgs mass of 125 GeV implies that the stop particle is at 8 TeV, which would already require fine-tuning of 1 part in 10^4 (Dine (2015)).

Yet another theoretical suggestion inspired by the naturalness principle is models that introduce extra dimensions (Arkani-Hamed et al. (1998); Randall and Sundrum (1999)). Models with large extra dimensions, for example, aim to solve the naturalness problem by bringing the scale of fundamental physics close to the scale of electroweak breaking. In the case where two dimensions are added, these models predict a modification of Newton's laws at millimeter scales and the creation of new particles on the order of 1 TeV. But results from proton–proton collisions at 13 TeV conducted at the LHC impose severe constraints on the viability of this approach (ATLAS Collaboration (2016)).

3. A change in attitude toward naturalness

The change in attitude toward the naturalness principle can be illustrated by looking at a series of programmatic publications authored by Gian Francisco Giudice, currently head of the theory division at CERN. Among other things, Giudice is concerned with the potential significance of the naturalness principle for the EFT framework. Before the experiments at the LHC had started, Giudice (2008) emphasized the central role of naturalness, stating that "[s]uch a correlation would signal a breakdown of the philosophy underlying the effective-theory approach" (165). After the first data from the LHC operating at 8 TeV had been collected, Giudice (2014) evaluated the significance of naturalness more cautiously: he still describes naturalness as a "very useful tool for physicists to make progress along the path towards the inner layers of matter"; however, he also states that the "naturalness principle is certainly not a *necessary* condition, indispensable for the internal consistency of [effective field] theory" (3).

A few years later, Giudice (2018) announced the "dawn of the post-naturalness era." He argues that the current state of particle physics can be described as a "turning point" or "crisis" (borrowing Kuhnian terminology) because the role of naturalness as a central guiding principle for BSM physics is threatened. According to Giudice, naturalness will play an important role even in the post-naturalness era, but he argues that new ways have to be found in order to drive progress in particle physics. Empirical research on physicists' attitudes toward naturalness appears to support that this change in attitude is a broader trend (Mättig and Stöltzner (2019)).

4. Explaining the change in attitude

In the philosophy of physics, there is now a vital debate about the credibility of naturalness as a guiding principle in particle physics. I do not seek to contribute to this debate. Instead I am interested in making sense of the change in attitude toward the naturalness principle. Such an explanation would have to account for (i) the central role that the naturalness principle played as a motivation for BSM proposals and (ii) the more recent perceived loss of significance of naturalness considerations.

Proponents of naturalness may explain why naturalness was so heavily employed by suggesting that naturalness was recognized as a substantial and well-founded principle at the heart of modern particle physics. Suppose that naturalness in the sense of autonomy of scales *is* required for the viability of the EFT framework. Suppose also that a majority of physicists concerned with BSM physics recognized that the naturalness principle had this status. Then physicists' employing the principle so heavily appears justified. Moreover, even if there are doubts today about whether naturalness arguments really are so well founded, the proponent of naturalness could still argue that before the absence of new physics was recognized, scientists did believe in the autonomy of scales being such an important requirement.

But there are problems with this explanatory approach. First, arguments for the substantial character of the naturalness principle tend to be exclusively based on an understanding of naturalness in the sense of the autonomy of scales. Williams (2015), for example, argues that the autonomy-of-scales formulation is a central dogma of the EFT framework, whereas the other formulations are much weaker and more vague. Yet all these formulations have been employed by scientists, often interchangeably. This indicates that the degree of reflection on the naturalness principle may be lower than assumed by this explanatory strategy (Borrelli and Castellani (2019)).

Second, it is not clear how the proponents' explanatory approach would account for the perceived loss of relevance of naturalness arguments. If naturalness arguments are such a substantial ingredient of modern particle physics (or even of physics in general), and if these arguments stand in conflict with experimental findings (or non-findings), then one should expect that naturalness problems become even more pressing now. Wallace (2019), for example, argues that the "apparent failure of naturalness is … a crisis at the heart of contemporary physics" (499f). It is certainly true that the absence of new physics at the LHC has led to renewed reflection on the foundations of the naturalness principle. Yet the kind of crisis that physicists like Giudice are concerned with appears to be of a much more pragmatic nature: now that physicists apparently cannot rely on naturalness anymore, new guiding principles are needed.

Opponents of naturalness will more easily address why naturalness arguments are less popular now. Yet opponents have difficulty explaining why naturalness arguments were so popular in the first place and why the absence of new physics was needed to convince physicists of the arguments' weaknesses. Opponents of naturalness, such as Hossenfelder (2018, 2021), have suggested that naturalness comes down to an aesthetic ideal that is widely spread but has little foundation, a circumstance that is related to certain structural features of the current high-energy-physics community. Such an explanation certainly has important virtues. Yet this leaves open whether there are also epistemic reasons for physicists' endorsement of the naturalness principle.

5. Forward-looking justification

Traditionally, principles are thought to be justified if they form a secure and robust basis of inquiry (Crowther and Rickles (2014)). However, philosophers of science have discussed a number of principles that are not justified in this way but rather through the potential to advance future inquiry. Friedman (2001), for example, argues that Newton's calculus and three laws of motion were not well entrenched or even controversial when they were first employed as constitutive principles of the new mechanics. The same holds, according to Friedman, for the mathematical theory of manifolds and the principle of equivalence employed by Einstein. Moreover, according to Massimi (2005), it was not the "humble" origin as a phenomenological rule of spectroscopy that justified the Pauli exclusion principle's status as a scientific principle but the systematizing role it played in the rising quantum mechanics. Certainly, each of these principles has roots in theories and practices that were well established. But, it seems, a full explanation of these principles' gaining their status as a principle cannot be given without reference to the role they have played in building new theoretical frameworks.

In what follows, I call this the *forward-looking justification* of scientific principles. In this mode of justification, scientists do not seek to support a principle merely with things they have learned in the past but take into consideration things that they may learn in the future. Usually, theories are justified by the fact that they can be derived or are in agreement with a principle. Here, the relation is at least partly reversed: scientists try to justify employing the principle because of its special relation to promising theories.

If particle physicists took the naturalness principle to be forward-looking justified, where was that justification believed to derive from? The physicist Michael Krämer (2013) suggests that the role of naturalness "had been strengthened in the last 25 years by the increasing evidence for the Standard Model Higgs mechanism, and by the progress in building viable SUSY models as a potential solution to the naturalness problem." So it appears that the principle of naturalness was taken to receive theoretical support because major proposals of BSM physics were thought to be in agreement with the principle.

One might want to object here that such agreement does not mean a lot in the cases of technicolor models and theories proposing extra dimensions, as well as low-energy SUSY, because these are natural theories *by construction*.[1] Yet one can imagine various ways in which such a construction could have failed to produce realistic models. For example, the theories could have turned out to run into straightforward inconsistency or to be in conflict with other important theoretical principles, such as conservation principles, or to be in conflict with experimental constraints available at the time of their development. Physicists' assessments of naturalness would certainly have differed if major proposals had already failed to solve the SM naturalness problem at the theoretical stage.

Usually, the naturalness principle has been seen as a justification for developing BSM proposals in the TeV regime. Wouldn't physicists who attempt to justify the naturalness principle with reference to such BSM proposals subscribe to an argument that is obviously circular? I agree that there is an important interdependence. Such an interdependence, however, does not necessarily undermine the potential for justification. Both the naturalness principle and SUSY have had independent support. SUSY theories were suggested independently of naturalness considerations and were considered promising because of gauge unification and weakly interacting massive particle (WIMP) dark matter. And naturalness was suggested independently of SUSY and has had further theoretical motivation.

Under these circumstances, consistent sets of beliefs and practices with inferential connections and joint explanatory power may be mutually supportive, according to coherentist epistemologies.[2] The naturalness principle and SUSY theories have a clear potential to be consistent, many physicists have taken the naturalness principle as an inferential basis to motivate SUSY, and SUSY would explain why certain parameters in the SM need to be finely tuned. Thus, the interdependence between naturalness and a BSM theory like SUSY may not have been perceived as a problematic circularity but rather as a relation of mutual support.

The perceived support is weakened by the absence of conclusive signs of new physics. As outlined in section 2, major BSM proposals made physicists expect new particles in the TeV regime currently probed by the LHC. The absence of such new physics in current experiments does not strictly exclude the viability of these theoretical frameworks. Even if SUSY is less popular than it was before the first tests, it is still an active field of research today. In particular, the absence of findings does not exclude alternative motivations for "unnatural" SUSY models (Arkani-Hamed et al. (2012)). The reasons to believe in a coherence between such theoretical proposals and the naturalness principle, however, are much weaker now.

The absence of new physics at the LHC suggests that major BSM proposals that were developed in response to the naturalness principle do not satisfy this principle after all. This coincides with a perceived loss of relevance of the naturalness principle

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[1] Because the first SUSY models were developed independently of naturalness considerations, one could argue that the support through coherence with SUSY is stronger than the support through coherence with the other theories because it involves what Dawid (2013) has called *unexpected explanatory coherence*.

[2] One suitable starting point for spelling out the interdependence in more detail could be the account of pursuit worthiness as indicated by potential coherence developed by Šešelja and Straßer (2014).

if high-energy physics moves to the "post-naturalness era," as suggested by Giudice (2018). Symptoms of such a loss of relevance are an increasing tendency to accept solutions that are simply fine-tuned and an increasing acceptance of attempts to explain fine-tuned parameters in a multiverse framework.

I conclude that a better explanation of the change in attitude toward the naturalness principle can be provided if we acknowledge that part of the perceived justification of the naturalness principle derives from forward-looking considerations. Before the discovery of the Higgs boson, the naturalness principle had given rise to a number of diverse and promising theories of BSM physics. The potential coherence between these theoretical proposals and the naturalness principle led to an increasing degree of credibility of the principle among particle physicists until the first experiments showed no signs of new physics. Since then, doubts have been raised with regard to the naturalness principle because the options of coherence between the principle and promising approaches like SUSY have become more and more limited.

Two qualifications are in order. First, this explanation, I believe, complements (rather than replaces) other explanatory approaches. The status of naturalness has been and still remains a controversial issue. There may be proponents of naturalness who argue that naturalness is more relevant than ever now that there is an apparent conflict with experimental results. Likewise, there have certainly been a variety of critical views on naturalness even well before this conflict. Second, this explanation is not intended to be a contribution to current debates about the actual credibility of that principle. It serves to make sense of the current shift in attitude toward naturalness independently of whether the world is in fact natural or whether a naturalness assumption was in fact beneficial to progress in high-energy physics.

6. Conclusion: Naturalness as a guiding principle

Even though the naturalness principle is often labeled as an important guiding principle, it has rarely been spelled out what that guidance consists of—apart from the fact that naturalness made physicists expect "new physics" in the TeV regime. One approach to spelling out the role of naturalness has been provided by Mättig and Stöltzner (2019), who characterize the current situation in high-energy physics as one that involves a form of underdetermination of theory by empirical evidence. In such a situation, it is argued, epistemic and pragmatic values are needed to decide which theoretical proposals are to be favored. In this context, Mättig and Stöltzner argue that the naturalness principle appears to fulfill the role of a pragmatic value: "It is an operationally relatively easy-to-apply quantitative criterion, at least once it is specified how much fine-tuning is allowed, and it constrains models; e.g. it suggests new particles with top flavour to compensate the main culprit for 'unnaturalness'" (93).

This pragmatic approach is more balanced than either the proponent's or the opponent's approach in that it admits that naturalness may never have had the solid foundation that some proponents have assumed but nevertheless might have had a legitimate role to play in theory building. But *why* did the naturalness principle gain the status of such an important guiding principle? The assumption that it is easy to apply is certainly not reason enough. Suppose that simplicity—another important and easy-to-apply theoretical virtue—is quantified by the degrees of freedom of a model. Then attempting to solve the SM naturalness problem by moving to the MSSM comes with a significant loss of simplicity. Thus, it seems naturalness appears to stand, at least sometimes, in a trade-off relation with simplicity (Dine (2015)). An account that approaches naturalness as a pragmatic virtue would then have to explain why the trade-off was decided—at least temporarily—in favor of naturalness. My account suggests that naturalness accrued credibility among particle physicists because of the support it received from the promising theoretical developments that it has inspired.

It remains an open question, though, how such mutual support is to be evaluated. Proponents of naturalness might want to see here a mechanism that has helped focus theoretical research on projects that appeared to be worthy of pursuit. Opponents of naturalness, by contrast, might want to stress that such a mutual reinforcement is a mechanism that can lead theoretical endeavors astray.

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