

Naturalness, Hierarchy, and Fine Tuning

Wednesday 28 February 2018 - Friday 02 March 2018

Aachen

Book of Abstracts

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A String Landscape Perspective on Naturalness

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It is an old idea that we may live in a multiverse. The fundamental parameters we observe in our local universe are then, at least to some extent, accidental. More recently, technical progress in superstring theory, which is arguably the leading candidate for a theory of quantum gravity, has given strong support to this idea. Concretely, the crucial progress came with the discovery of a very large set of effectively 4-dimensional solutions of the 10-dimensional superstring, the so-called “String Theory Landscape”. Moreover, the dynamical mechanism of Eternal Cosmological Inflation is apparently capable of populating the above Landscape. This provides a very concrete, technical realization of the multiverse. Obviously, such a scenario has direct implications for the discussion of naturalness in quantum field theories as they emerge in the low-energy limit of string theory. However, concrete progress is still difficult since, on the one hand, the Landscape is extremely large and complex and our calculational ability limits detailed analyses to small corners of this set of solutions. On the other hand, it turns out to be highly non-trivial, even in principle, to predict where we should expect to find ourselves in this multiverse. This so-called Measure Problem makes it hard to state unambiguously “what is natural” in the Landscape. In my talk, I will attempt to explain the above set ideas in an elementary way and to discuss what a string-theoretic perspective on naturalness or fine-tuning issues in the Standard Model may be.

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Finetuning and Free Parameters

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The paper discusses the way in which the perspective of a universal fundamental theory without free parameters changes the role of finetuning arguments in physics. It has been suggested that finetuning arguments merely express aesthetic preferences. The assumption of a fundamental theory without free parameters allows for a substantially stronger role of finetuning arguments that is more reminiscent of stating low p-values in hypothesis testing. This is consistent with the broader view that an adequate understanding of the significance of finetuning arguments must account for the nature and status of expectations with regard to the next levels of fundamentality.

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Matter in a Multi-Component Universe, Naturalness and the Quest for a Fundamental Theory

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Finetuning describes unlikely coincidences on an effective level of description which are expected to be explained in a more fundamental theory. In this talk a fresh view on the topic of Naturalness and Finetuning is presented which is based on a “holistic” concept for the most fundamental layer of reality. We start with recent research on the abundances of leptons, baryons and dark matter in the Universe. As we have shown, it turns out that what appears to be finetuned or contradictory if only individual matter species are considered may be resolved in a multi-component approach, taking into account the interplay of all contributions to the total energy density of the Universe. This rather trivial example can be generalized to the relation of subsystems to the Universe in quantum cosmology. Adopting a universal applicability of quantum mechanics, in this framework the behavior of subsystems can be understood as the perspectival experience of an entangled quantum Universe perceived through the “lens of decoherence”. In this picture the fundamental reality is non-local, and finetuned coincidences in effective theories may be understood in a way similar to EPR-correlations.

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Naturally Light Scalar Particles: A Mechanism Involving Dangerously Irrelevant Discrete Anisotropies

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The hierarchy problem in the Standard Model is usually understood as both a technical problem of stability of the calculation of the quantum corrections to the masses of the Higgs sector and of the unnatural difference between the Planck and gauge breaking scales. Leaving aside the gauge sector, we implement on a purely scalar toy model a mechanism for generating naturally light scalar particles where both of these issues are solved. In this model, the scalar particle is a pseudo-Goldstone whose mass comes from a highly non-renormalizable term that explicitly breaks the continuous symmetry down to a discrete one. Being discrete, the spontaneous breaking of the symmetry does not generate vanishing masses. However, the non-renormalizable character of the term of explicit breaking drives through quantum corrections the mass of the would-be Goldstone to a very small value without fine-tuning.

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Naturalness - How Religion Turned into Math

Sabine Hossenfelder^{None}

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Naturalness arguments have been extremely influential in the foundations of physics during the last decades. I explain why they are based on faulty reasoning.

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Naturalness and Analogies to Condensed Matter Physics

Doreen Fraser¹

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Over the past century, a fruitful strategy for constructing new models in both particle physics and condensed matter physics has been to develop analogies between theories for the two domains. Two of the theoretical components at the heart of naturalness arguments in particle physics were inspired by analogies with condensed matter physics: renormalization group (RG) methods (which are central to the effective field theory approach) and spontaneous symmetry breaking. In both cases, the analogies are purely formal. That is, the analogical mappings between the particle and condensed matter physics models relate elements that play similar formal roles in the mathematical structures, and there are no underlying physical analogies between the mapped elements. In fact, there are substantial physical disanalogies between analogous elements of the models. After surveying some of the relevant pragmatic, empirical, and physical differences between applications of the formalisms in the two domains, I will critically examine the role that analogies to condensed matter physics play in naturalness arguments in particle physics.

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Naturalness and Supersymmetry: a Historical-Philosophical Perspective

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No evidence of “new physics” in general and supersymmetry in particular was found so far by LHC experiments, and this situation has led some voices in the physics community to call for the abandonment of the “naturalness” criterion, while other scientists have felt the need to break a lance in its defense by claiming that, at least in some sense, it has already led to successes and therefore should not be dismissed too quickly, but rather only reflected or reshaped to fit new needs. In our paper we will argue that present pro-or-contra naturalness debates miss the fundamental point that naturalness, despite contrary claims, is essentially a very hazily defined, in a sense even mythical notion which, in the course of more than four decades, has been steadily, and often not coherently, shaped by its interplay with different branches of model-building in high-energy physics and cosmology on the one side, and new incoming experimental results on the other. A particularly important factor in this constellation, albeit by far not the only one, was the rise of supersymmetry from the 1980s onward. In our paper we will endeavor to clear up some of the physical and philosophical haze by taking a closer look back at the encounter and interplay between naturalness and supersymmetry, starting from the 1970s, when the search for “natural” particle models and “natural” solutions to the hierarchy problem of Grand Unified Theories began, to the rise to prominence of the “unnatural” Higgs mass divergences, up to and beyond the time when a facet of naturalness was co-opted as a criterion for supersymmetric

model-building. In doing this, we aim to bring to light how naturalness belongs to a long tradition of present and past physical and philosophical criteria for effectively guiding theoretical reflection and experimental practice in fundamental research.

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Naturalness as a Value of Theory Preference

Michael Stöltzner ¹

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The principle of naturalness seems to be a mysterious dweller in the edifice of contemporary particle physics. It has been given different formulations that were aptly dissected by philosophers. But the community itself seems to consider the naturalness problem as a largely coherent guide for model builders. As such, naturalness has come under pressure through the observation of the Higgs boson and the dramatically reduced parameter space for all physics beyond the Standard Model that could be a candidate to solve the naturalness problem. But naturalness is too closely connected to other key concepts and principles of particle physics to go away like a worn-out story, a narrative that keeps together what has long fallen apart. The era of post-naturalness that Giudice has recently proclaimed is still chiefly shaped by the naturalness and, accordingly, far away from the incommensurability required for a Kuhnian revolution.

My paper intends to provide a basis for discussing naturalness by interpreting it as a complex value of model preference. Such cognitive values or criteria can be epistemic or pragmatic; default examples are empirical adequacy or simplicity respectively. In a field as complex and parameter-rich as contemporary particle physics, empirical values usually leave wiggle room until a model can be considered confirmed and its competitors are squeezed out from the parameter space. In the Higgs sector, naturalness starts out as an empirical value of preference – from the specific problem a scalar particle presents for the theory’s consistency – that prompts a pragmatic value, the amount of fine-tuning one is willing to accept. If one abandons the idea to pit rational justification against historical happenstance – that still lingers in some discussions on values of preference – there is nothing problematic about such complex values.

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Naturalness, Finetuning, Fixed Points, and the Likelihood of a Theory

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A key role that naturalness plays in particle physics is the narrowing of focus and the status elevation of speculative theories. There are several ways a speculative theory’s status can be elevated, including the assessment that it is more likely than other speculative theories. It is argued that naturalness claims on speculative theories are just those – claims that natural theories are more likely than unnatural theories. Yet, putting such claims on firm statistical foundation requires knowledge of an a priori statistical distribution of theory parameters, which constitutes disquieting additional speculative input beyond normal theory construction. The role of fixed points is also considered, which may provide answers relatively independent of parameter distributions. It is also discussed how useful finetuning is as a numerical functional for naturalness assessments. Finally, it is argued that a central implication of naturalness skepticism is that the likelihood status of any speculative

theory should not be diminished when there is at least one concordant theory point in parameter space remaining.

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Naturalness, Wilsonian Renormalization, and ‘Fundamental Parameters’ in Quantum Field Theory

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Increasingly strong indications from the LHC that the Standard Model violates the naturalness principle raise several possibilities: 1) failure of naturalness is a genuinely problematic feature of the Standard Model that we should seek to correct in the search for deeper theories, 2) failure of naturalness is problematic, but a contingent fact of nature that we must simply accept, 3) failure of naturalness is unproblematic, and the naturalness principle should be abandoned. Exploring the third possibility, we closely examine one influential and inter-connected set of justifications for imposing naturalness in the particular senses that prohibit fine-tuning of the bare Higgs mass and delicate sensitivity to slight variations in bare parameters at the Standard Model’s physical high-energy cutoff. We highlight the dependence of these justifications on the physical interpretation of these bare parameters as “fundamental parameters,” which draws heavily on the well-known analogy between elementary particle physics and condensed matter theory. We argue that while failure of naturalness in these senses is legitimately regarded as problematic on this interpretation, there remains a viable alternative physical interpretation of these parameters that is under-recognized within the literature on naturalness, according to which there is nothing problematic or “unnatural” about the fine tunings or sensitivities in question. On this interpretation, all bare parameters, including those at an effective field theory’s physical cutoff, are unphysical “auxiliary” parameters. We argue that this interpretation may be more appropriate to the context of elementary particle physics, implying that, despite the strong mathematical analogies between the quantum field theoretic formalisms of condensed matter theory and elementary particle physics, the particular forms of naturalness-based reasoning discussed here are undermined by strong *disanalogies* of physical interpretation of the formalism in these different contexts.

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Naturalness, critical phenomena and new routes to UV-complete theories

The hierarchy problem and thus the absence of technical naturalness in the standard model is not an inconsistency of our theoretical description of fundamental physics, but may rather be viewed as an aesthetic blemish. Renormalization theory of critical phenomena suggests that the amount of unpleasantness can be quantified by critical exponents which are intrinsic properties of a particle physics model. Attempts at solving/beautifying the hierarchy problem can be classified in terms of how critical exponents are modified.

Abandoning aestheticism as a primary motivation, I argue that new routes to theoretical consistency should be searched for - accompanied by a sound view on the available experimental data. I suggest that novel constructions of asymptotically free theories with gauge and Yukawa sectors are a promising direction which can provide new ingredients for model building. Such constructions have recently been identified, leading to UV complete quantum field theories and Higgs interaction potentials approaching asymptotic flatness. The critical exponents of such theories are computable and show novel features of exact marginality.

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On the Hierarchy Problem and the Cosmological Constant Problem in the Standard Model

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I argue that the SM in the Higgs phase does not suffer from a "hierarchy problem" and that similarly the cosmological constant problem resolves itself if we understand the SM as a low energy effective theory emerging from a cut-off medium at the Planck scale. We discuss these issues under the condition of a stable Higgs vacuum, which allows to extend the SM up to the Planck length. The bare Higgs boson mass then changes sign below the Planck scale, such that the SM in the early universe is in the symmetric phase. The cut-off enhanced Higgs mass term as well as the quartically enhanced cosmological constant term trigger the inflation of the early universe. Reheating follows by the heavy Higgses decaying predominantly into top-anti-top pairs, which at this stage are effectively massless. The coefficients of the shift between bare and renormalized Higgs mass as well as of the shift between bare and renormalized vacuum energy density exhibit close-by zeros at about 10^{15} GeV. The scale dependent Higgs mass counter term is negative in the Higgs phase (low energy), which triggers the electroweak phase transition, and changes sign at the transition point after which it is large positive, which turns the system into the symmetric phase at high energies. Obviously, the SM Higgs system initially provides a huge dark energy density and the resulting inflation is taming the originally huge cosmological constant to the small value observed today, whatever its initial value was, provided it was large enough to trigger inflation. While laboratory experiments can access physics of the broken phase only, the symmetric phase above the Higgs transition point is accessible through physics of the early universe as it manifests in cosmological observations. The main unsolved problem remains the origin of dark matter.

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Scales and Hierarchies in Asymptotic Safety

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Asymptotic Safety provides a possible mechanism for a consistent and predictive high-energy completion of gravity and gravity-matter theories. The key ingredient in the construction is an interacting renormalization group fixed point which controls physics at trans-Planckian scales. Relevant couplings have the task of identifying a given asymptotically safe theory within the unstable manifold of this fixed point. In this talk I will summarize the basic ideas underlying the construction and discuss the cosmological constant problem and hierarchy problem based on this fundamental perspective.

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Simplicity and Effectiveness in Physics of the Unknown

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If physics is a science that unveils the fundamental laws of nature, then the appearance of mathematical concepts in its language can be surprising or even mysterious. This was Eugene Wigner's argument in 1960. The debate on naturalness brings forth a tension between the values of effectiveness and simplicity of the mathematical formalism. On the examples of the S-matrix approach in quantum field theory and effective field theories, I show how one builds a theory from fundamental principles, employing them as constraints within a general mathematical framework. The rise of such theories of the unknown ("blackbox" or "device-independent" models) drives home the unsurprising effectiveness of mathematics.

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Successes of Naturalness

Undeniably, the naturalness principle, acting as a guiding principle, has had a major role in particle physics during the last decades, in particular in model building. Nowadays, one can find a wide range of different definitions, some of them seem mutually exclusive, but traditionally its notion has been linked to the fine-tuning problem. Its operational definition can be stated as the imposition that the fine-tuning problem has to vanish, for instance, due to the existence of new particles in the scale in which fine-tuning problems start to appear. Therefore, in order to palliate the fine-tuning problem that the Higgs sector of the standard model seems to suffer, new physics should have already appeared in the last LHC run. Its persistence has originated numerous works exploring both, the limits and the different conceptual definitions of naturalness. However, little work has been done re-examining precisely one of the main pillars naturalness advocates: its historical successes. Given the current period in which the critics to the naturalness principle are undergoing, it is important to explore the historical examples often cited in literature, primarily the charm quark proposal and its mass prediction and how they are related to the fine-tuning problem in the Higgs sector.

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Two Notions of Naturalness

Porter Williams¹

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My aim will be to distinguish two notions of naturalness in use in BSM physics. One way of understanding naturalness is as a prohibition on sensitive dependencies of a theory's description of low-energy physics on details of the theory's description of high-energy physics. I will argue that considerations from the general structure of effective field theory provide motivation for this notion of naturalness. A second way of understanding naturalness is as a requirement that the values of the parameters in a quantum field theory, such as the Higgs mass, be "likely" (for some appropriate measure) in some appropriately circumscribed space of models. The two notions are clearly related but strike me as motivated by distinct theoretical considerations and, furthermore, may admit of distinct kinds of solution.

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Welcome

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Why Be Natural?

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I consider four reasons to adopt the criterion of naturalness in the context of effective field theories (EFTs) of fundamental phenomena, the first three less compelling than the fourth. The first three are (i) naturalness has had modest empirical success, (ii) it can be quantified, and (iii) it is consistent with an image of EFTs that is underwritten by what Williams (2015) calls a "central dogma"; namely, that phenomena at widely separated scales should decouple. I argue that these are not compelling reasons because (i) despite its modest empirical success, naturalness has had spectacular empirical failures; (ii) subjectivity plays a large role in defining a quantitative measure of naturalness, and if the intent is to demonstrate how unlikely unnaturalness is (how unlikely fine-tuned parameters are, for instance), then this risks begging the question; and (iii) there are versions of EFTs that, arguably, are not governed by the central dogma; namely, what Georgi (1993) calls continuum EFTs. On the other hand, a fourth reason to be natural is that naturalness underwrites a non-trivial notion of emergence. Naturalness, as an insensitivity of low-energy degrees of freedom to the dynamics of high-energy degrees of freedom, might be associated with a notion of robust dynamical independence, and one might argue that the latter is a necessary condition for emergence (the other being some form of dependence condition). Thus to the extent that one desires to interpret the phenomena described by an EFT as emergent, one should desire to be natural. The general moral is that naturalness should be considered an empirical hypothesis with ontological implications; thus, given its current empirical status with respect to the Standard Model, caution, but not prohibition, should be urged in using it as a guiding principle for theory construction.

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