# 2.4.4.1 Technical, fundamental and epistemological limits of science

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In recent decades, a gap between two kinds of physical reasoning has opened up. Applied and phenomenological physics show all basic characteristics of canonical 20th century science. But fundamental physics, represented by high energy physics model building, quantum gravity and cosmology, faces substantially new challenges that influence the nature of the scientific process. Those shifts can be expected to become even more conspicuous in the period up to 2050. Exploring their full scope will arguably be an important task for fundamental physics in upcoming decades.

The 20th century was a hugely successful period in fundamental physics. Developments from the advent of relativistic physics and quantum mechanics to advanced theories in particle physics played out based on the general expectation that physicists would find theories that could account for the collected empirical evidence in a satisfactory way and could (with some exceptions) be empirically tested within a reasonable time frame. In stark contrast to the 18th and 19th centuries' absolute trust in Newtonian mechanics, however, 20th century physicists assumed that none of the theories they were developing would be the last word on the general subject they addressed. Theories successful at the time would eventually be superseded by more fundamental ones. Physicists thus were highly optimistic about their future achievements but avoided declarations of finality with regard to any theory at hand.

Early 21st century physics finds itself in a very different place. The following pages will focus on three aspects of the new situation: the long periods of time in which influential theories remain without empirical testing; the long periods of time in which theories remain conceptually incomplete; and the issue of finality in contemporary physics.

## 1: Limits to empirical access

In high energy physics, the last theory that has found empirical confirmation is the standard model, which was developed in the late 1960s and early 1970s. The empirical confirmation of the standard model's many predictions was completed in 2012 with the discovery of the Higgs particle.[1] Theory building from the mid-1970s onwards has reached out far beyond the standard model, however. New theories were motivated in various ways. Some characteristics of the data, though not contradicting the standard model, found no satisfactory explanation on its basis. More substantially, quantum field theory, which provided the conceptual foundation for the standard model, is inconsistent with general relativity, the theory that described gravity. General characteristics of gravity imply that the strength of the gravitational interaction becomes comparable to the strength of nuclear interactions at a high energy scale (called the Planck scale). To describe physical processes at that scale, a new theory is needed that describes gravity and nuclear interactions in a consistent way.

During the last 50 years, the described lines of reasoning in conjunction with others have led to the development of influential theories beyond the standard model. Grand unified theories (GUTs), supersymmetry and supergravity introduce larger symmetries within the context of gauge field theory. String theory aims at full unification of all fundamental interactions by reaching out beyond the confines of conventional gauge theories. Various conceptual approaches aim at the quantization of gravity from a general relativistic starting point. In cosmology, the theory of inflation provides an entirely new view on the very early phase of the universe.

Up to this point, none of the mentioned theories has achieved empirical confirmation of its core predictions. Nevertheless, some theories have been quite strongly endorsed by its exponents. The most striking example is string theory [1], which was presented in 1974 as a fundamental theory of all interactions based on replacing the point-like elementary particles of quantum field theory by extended one-dimensional objects, the strings. From the late 1980s onwards, it has assumed the status of a conceptual basis and anchoring place for much of fundamental physics. Exponents of string theory think they have very strong arguments for the theory's viability even in the absence of empirical confirmation. [2] Critics of string theory, on the other hand, deny any epistemic justification for an endorsement of the theory in the absence of empirical confirmation [3].

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[1] The only data-driven adaptation of the standard model happened in the late 1990s when the massiveness of neutrinos was empirically established. That feature could be accounted for within the standard model framework in an entirely coherent way, however.

[2] Contact between string theory and characteristics of our world that does not reach to the level of significant confirmation has been made in the research field of string phenomenology [2].

A slightly different case is cosmic inflation [4]. The theory of cosmic inflation lies at the core of large parts of contemporary cosmological reasoning. It aims to explain some very general features of the universe that would seem a priori inexplicable within the context of general relativity, and to account for characteristics of cosmological precision data. To that end, it posits an early phase of extremely fast (exponential) expansion of the universe. Unlike string theory, quantitative implications of models of cosmic inflation can be confronted with empirical precision data. The theory is widely taken to be in very good agreement with available cosmological data. Many of the theory's exponents have a high degree of trust in the hypothesis of inflation on that basis. Critics of inflation take that trust to be unjustified, however. They emphasize the theory's lack of conceptual specificity and doubt the confirmatory value of seemingly supporting empirical evidence [5].

Maybe the most fundamental problem for conclusive empirical confirmation arises with respect to the multiverse hypothesis [6][3]. Based on conceptual considerations in inflationary cosmology, the multiverse hypothesis posits that vast numbers of universes are generated in an exponentially expanding background space. We live in one of those many universes and, according to the present understanding, cannot possibly make any observations beyond the limits of our own universe. The existence of the other universes therefore may be inferred based on theoretical considerations but can never be empirically confirmed. Exponents of the multiverse point out that there can be empirical confirmation of the multiverse theory based on the theory's predictions regarding our own universe. Critics of the multiverse argue that the in-principle lack of empirical access to core objects posited by the multiverse hypothesis nevertheless infringes on the principle of testability of scientific theories [7].

In all three described contexts, physics faces the problem how to deal with the absence of or with complications regarding the empirical testing of fundamental physical theories. These problems can be expected to continue in upcoming decades and raise the general question as to what counts as a viable epistemic basis for seriously endorsing a scientific theory. Obviously, the scientific process will sustain its efforts to develop effective strategies for empirical testing wherever possible. Empirical confirmation will remain the ultimate and most trustworthy basis for endorsing a theory. The question will become increasingly important, however, how to assess the status of well-established theories in the absence of sufficient empirical confirmation. A research process where scientists often spend their entire career working on a theory without seeing that theory conclusively empirically tested raises this question with urgency. Characteristics of fundamental physics today may indeed offer a basis for epistemic commitment that reaches out beyond the canonical confines of empirical confirmation. A philosophical

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[3] The multiverse plays a pivotal role in the influential and much debated anthropic explanation of the finetuned cosmological constant.

suggestion to that end has been presented under the name non-empirical (or more specifically meta-empirical) confirmation [8].

As described above, scientific praxis in recent decades has led many theoretical physicists towards having substantial trust in empirically unconfirmed or inconclusively tested theories, while other physicists have strongly criticized that process. The developments in physics in upcoming decades will move this issue forward, one way or another. If further developments vindicate trust in theories such as string theory or cosmic inflation based on empirical confirmation, non-empirical arguments, or both, this will increase the willingness of theoretical physicists to strongly endorse theories even in the absence of strong or any empirical confirmation. In that case physical reasoning in 2050 will be based on a significantly extended concept of theory confirmation. If trust in the above theories erodes for whatever reason, the focus will move back towards a more traditional understanding of theory assessment.

## 2: The chronical incompleteness of fundamental theory building

The second problem faced by fundamental physics may be even more significant from a conceptual point of view: fundamental theories in physics become increasingly difficult to spell out in a complete form. In some cases, for example in the case of cosmic inflation, this problem is directly linked to the theory's limited empirical accessibility that stands in the way of specifying the conceptual details of the theory in question. But in other cases, such as string theory, the core of the problem seems distinct from issues of empirical access.

String theory has been conceptually analyzed since the late 1960s and proposed as a theory of all fundamental interactions in 1974. 55 years of work on string theory, including four decades when a substantial part of the theoretical physics community has contributed to developing the theory, have not brought string theory anywhere close to completion. The theory today amounts to an enormously complex system of conjectures, elements of formal analysis and calculations achieved based on simplifications or approximations. In conjunction, these strands of analysis provide a considerable degree of understanding of the coherence and cogency of the overall approach and the ways in which many of its aspects are intricately related to each other. Still, the theory's core remains elusive.

As described above, the development of the conceptual understanding of string theory has not found guidance by empirical data. Such data, if available, would obviously be very helpful for further conceptual work on the theory. It would not in itself provide the basis for solving the conceptual core problem, however: how to pin down the full formal structure of string theory.

The difficulties to develop a full-fledged string theory have their roots in quantum field theory, the theory that has been developed to describe interactions between highly energetic (that is very fast-moving) elementary particles since the 1930s. Calculations of specific quantitative empirical implications of quantum field theories can only be extracted based on perturbation theory, which is a method of approximation. Perturbation theory provides highly accurate and reliable quantitative predictions of specific particle interaction processes if the interactions involved are weak (in a well-defined sense). For strong interactions, the method breaks down. String theory was initially developed as a perturbative theory along the conceptual lines of perturbative quantum field theory. Two aspects of string theory render the use of perturbative methods more problematic than in the case of quantum field theory, however. First the full theory to which perturbative string theory is an approximation is still unknown. Therefore, perturbative string theory does not merely serve as an approximation scheme but also as an essential indicator of the character of the unknown theory to which it is supposed to be an approximation. Second, string theory has no (dimensionless) free parameters. Therefore, interaction strength, like all other parameters of low energy physics, must emerge from the full dynamics of the theory. Thus, the reliability of the perturbative method cannot be a universal feature of string theory. At best, it could be extracted for a given regime from a non-perturbative analysis of the fundamental theory. Compared to conventional quantum field theory, the understanding of string theory thus is overly dependent on a perturbative perspective while there is a more urgent need to reach out beyond it.

Recent decades have led to a deeper understanding of string theory that reaches out beyond the perturbative perspective. A crucial role in these developments is played by duality relations that establish weak and strong coupling regimes of seemingly entirely different types of string theory (and beyond) to be empirically equivalent [9]. No breakthrough towards a full understanding of the mechanisms that guide non-perturbative string theory has been achieved, however. The elusiveness of a full formulation of string theory, at its core, in this light is a conceptual problem rather than a problem of empirical access.

The problem is not confined to string theory. All approaches to quantum gravity that choose different starting points than string theory, such as loop quantum gravity or spin foam, have encountered similar problems. After decades of work on those approaches, they have not led to a complete theory. It is not even clear whether a coherent theory of gravitation in four extended spacetime dimensions can be formulated based on those approaches.

The problem thus seems to arise once theory building aims at the level of universality needed to join the principles of quantum physics necessary for understanding microphysical phenomena with the principles that govern gravity. While 20th century physics has achieved a satisfactory understanding of those two realms of fundamental physics in separation, the 21st century may be expected to be devoted to bringing them into a coherent overall conceptual framework. It is exactly this context where the substantial roadblocks described above arise.

It will be the main task of fundamental physics in the upcoming decades to further attack those difficulties. But the substantial shift in the time scales for completing theories of fundamental physics may lead fundamental physics towards re-evaluating its understanding of scientific progress altogether. Since the 19th century, this understanding has been based on the principle of theory succession: theories are being developed within a reasonable time frame, to be empirically tested soon thereafter. Empirical tests could either lead to the theory's rejection or to its confirmation as a viable description of nature within a given empirical regime. Further tests would then test the theory's predictions with increasing accuracy until a disagreement between data and the theory's predictions was found. Such empirical anomalies could then lead to the development of a new theory that replaced the old one as the viable fundamental theory.

The first part of this text has indicated that the timelines for empirical testing have been stretched to an extent that renders the canonical view of the scientific process insufficient. The present section points out that the canonical view is drawn into question at a conceptual level as well. Scientific progress in 21st century fundamental physics may not amount to formulating complete scientific theories.

Today, this shift of perspective is merely a possibility. It may still happen that, by the year 2050, revolutionary changes in physics will have turned a full theory of quantum gravity into an imminent prospect or even into reality. If so, the current suspicion of a long-term change of theory dynamics would have turned out to be a transient impression provoked by a particularly difficult phase of theorizing.

If, however, the period up to 2050 prolonged the current step by step conceptual progress towards a better understanding of an elusive theory of quantum gravity, this would strengthen the case for acknowledging a lasting and substantial shift in the scientific dynamics of fundamental physics: the process of theory succession that characterized 19th and 20th century physics would seem to have been replaced by a different mode of the scientific process that is represented by continuous work on and an improving understanding of one theory or theoretical framework without prospects of formulating a complete theory in the foreseeable future. The completion of that theory would appear as a remote endpoint of the process of physical conceptualization rather than an imminent goal for the individual scientists. To what extent that new dynamics amounted to a manifestation of fundamental limits to science and to what extend it should rather be viewed in terms of an altered concept of scientific progress, would then emerge as a core question for the status of physics in the 21st century.

## 3: Signs of finality

A third important shift that has occurred in fundamental physics in recent decades is directly related to the issue of acknowledging a new phase of the scientific progress: fundamental physics today is more conspicuously associated with issues of finality of theory building [10] than 20th century physics.

Throughout much of the 20th century, physics shunned any suggestion of finality in physical theory building for two reasons. First, the revolutions of special and general relativity and quantum mechanics served as omnipresent reminders that even with regard to a theory that was as dominant, successful and long-living as Newtonian mechanics, claims of finality had been misplaced. Second, it became increasingly clear that the incoherence between the principles of quantum mechanics and general relativity would require at least one more fundamental conceptual step before arriving at a fully consistent overall understanding of theoretical physics. All empirically successful theories in 20th century physics were therefore understood to be viable at most up to those energy scales where predictions had to account for gravity and nuclear interactions at the same time.

When attempts to develop a theory of quantum gravity took center stage in fundamental physics in the last quarter of the 20th century, this situation changed. The second reason for not considering issues of finality ceased to apply since quantum gravity amounted to the projected conceptual step that had prevented finality claims regarding previous theories. Moreover, the appeal of the first reason was considerably weakened as well. Quantum gravity provided new reasons for taking finality claims seriously that went beyond anything that could have been said in support of the finality of Newtonian mechanics in the 19th century. 19th century finality claims regarding Newtonian mechanics were based simply on the enormous and longstanding success of the theory in multiple contexts and the lack of evidence that suggested that it needed to be superseded. The empirical testing of processes where very high velocities, very small objects, or very high gravitational force were involved did eventually reveal empirical inconsistencies with Newtonian mechanics that led to the revolutionary new theories that superseded it. Nothing in Newtonian physics apart from a crude meta-inductive assumption that a theory that has worked in so many contexts should work everywhere would have, in advance, spoken against the possibility of such an outcome.

General considerations on the nature of quantum gravity provide a stronger basis for a final theory claim. To understand the basic idea, one needs to remember once again how physics has changed in the 20th century. From a 19th century perspective, velocities, distances, and mass values were independent parameters. Special relativity then established that an object's mass was a form of energy (just like its kinetic energy) and quantum mechanics allowed to view distance scales in terms of inverse energy scales. The move towards higher energy respectively smaller distance scales thus became the one central guideline for finding new phenomena in fundamental physics. Quantum gravity now suggests that the notion of distance scales smaller than the scale where gravity becomes roughly as strong as nuclear interactions (the so-called Planck scale) may not make sense due to a fundamental limit to information density. String theory, viewed by the majority of physicists to be the most promising approach of quantum gravity, offers a deeper understanding of this limit (in terms of a specific feature called T-duality) [11]. These arguments do not conclusively establish finality because their soundness relies on the truth of the theory or conceptual framework on whose basis they are developed. Nevertheless, they turn questions of finality into genuinely physical questions.

The issue of finality stands in a complex relation to the issue of chronical incompleteness addressed in the previous section. On the one hand, chronical incompleteness makes it more complicated to understand what could even be meant by a final theory claim. How is it possible to assert the finality of a theory whose full formulation is not in sight? At a different level, however, the final theory claims raised in quantum gravity seem in tune with the phenomenon of chronical incompleteness. Like chronical incompleteness, final theory claims may be taken to suggest that the paradigm of scientific progress that was prevalent throughout the 20th century is inadequate for characterizing the scientific process in 21st century fundamental physics. Based on the canonical paradigm of scientific progress, a final theory claim regarding a universal theory like string theory would imply the completion of fundamental physics within the foreseeable future. Once one replaces that canonical paradigm by a principle of chronical incompleteness, however, nothing of this kind follows. On that view, the projected point in time when fundamental physics will have been completed has not come closer. What has changed is the nature of the scientific process that leads towards that point: rather than a sequence of superseding complete theories, it would be step-by-step progress towards an improved understanding of the one universal and final theory physicists are working on already but whose completion is not in sight.

If the upcoming decades of physical research strengthen the tendencies described in this text, fundamental physics in 2050 will be a very different enterprise than fundamental physics half a century ago. Its new character will arguably change the human understanding of the nature of scientific reasoning. The three described developments are distinct but carry a coherent overall message. As long as physics deals with limited sets of phenomena, it is the physicist’s task to identify those phenomena that allow for the development and empirical testing of appropriate theories within a reasonable time frame. Once physics approaches a fully universal fundamental theory, however, leaving out what seems too difficult to include stops being an option. Physics thus faces a situation where problems too difficult to solve and phenomena too remote to be empirically tested at the given point all live within the scope of the universal theory that is being developed. Achievable research goals in this new environment shift from the complete formulation and the conclusive testing of the theory towards the more modest goals to solve specific problems within the overall theory, confront the theory with empirical data to the extent possible, and assess the theory's status based on all information available. Within this new framework, just like before, physics will pursue its old but still distant ultimate goal: to find a full and consistent description of the physical world we live in.

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