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Forty Years of String Theory Reflecting on the Foundations

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1 Introduction

The history of string theory started around 1970 when Nambu, Nielsen, and Susskind realized that Veneziano's 1968 dual model, devised to explain the particle spectrum of the strong interactions, actually describes the properties of quantum mechanical strings. A few years later, QCD appeared as a superior model for the strong interactions; furthermore, in 1974 it was realized that strings contain gravitons in their spectrum. For these reasons, many lost interest in the theory, while for some it made an interesting candidate as a unifying theory of gravity and quantum field theory.

Since then, string theory has undergone several metamorphoses and is regarded by the majority of the community as the most promising quantum theory of grav-

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ity. Among its results are microscopic computations of black hole entropy and the suggested implication, acknowledged by Hawking, that black holes do not violate quantum theory; spectacular success in describing perturbative and non-perturbative aspects of gauge theories; the holographic description of gravity realized in string theory, which has led to key conceptual insights in understanding gravity and geometry; it has also provided new ideas and tools in cosmology, such as the existence of a finite number of false vacua (the so-called 'string theory landscape'). String theory has also shown its ability to shelter under its umbrella entire fields which at first were seemingly disconnected from it, such as supergravity and black holes. It has established new connections between field theories and gravity and far-away disciplines such as mathematics, condensed matter, and fluid dynamics; especially in mathematics, string theory has produced astonishing results such as the mirror symmetry conjecture. For these reasons, string theory is described by many as a 'framework' rather than a theory.

Today, string theory is a mature field that has produced an unprecedented amount of work and new ideas in theoretical physics. Yet string theory is neither a complete theory nor free from criticisms, as the present special issue reflects. Among the shortcomings mentioned by our authors, there are the lack of directly testable experimental predictions that would signal 'string physics'. Another, and in some respects more disturbing problem, is that a fundamental formulation of string theory is not yet known—not only in the mathematical way or rigor, but even in the physical sense of finding the 'fundamental variables' of the theory. Therefore, calling string theory a 'theory' deserves qualification. Such qualification is provided by our authors, who not only review current progress in this direction, but also reflect on what the meaning of 'fundamental variables' for a final theory might be.

Another topic widely discussed in this issue is the sense in which string theory is a theory of quantum gravity, and in particular the extent of its background dependence. Non-string theorists and string theorists alike discuss this issue. The landscape is also discussed, a topic that—as several others—is regarded by some as a virtue and by others as a vice.

Finally, some critics have pointed out that sociological issues are also at stake in the way string theorists are doing science: in this view, string theory monopolizes the best jobs in the academic career market, so that young talented researchers have no choice but following the trends if they want to have a chance of an academic career. These concerns are addressed in one of our contributions.

Criticism of string theory has recently impacted the popular science media. Discussions of the foundations of string theory have however been virtually absent from the scientific literature. It is therefore time for the scientists involved in string theory and quantum gravity, as well as philosophers of science, to discuss the foundational issues relevant to string theory. Scientific journals are the proper place for this discussion. Science progresses through new models and ideas; string theory has been prolific in this respect in the last forty years. Discussions of the foundations of theories are however just as important, for they clarify the meaning of those theories; they identify hidden assumptions or weaknesses and suggest new directions.

In this Special Issue of Foundations of Physics, string theory experts will reflect on the current status of the theory; what has been achieved, what are the key unresolved issues, the strengths of the theory and its weaknesses; what directions for the future. Other quantum gravity experts also assess the theory and compare it to their own theories or models. Philosophers comment on the status of string theory both from the ontological point of view and as a scientific theory.

The special issue is divided in the following sections:

(a) Critics:
  1. Carlo Rovelli: *A look at string theory from the perspective of quantum gravity.*
  2. Lee Smolin: *A perspective on the Landscape Problem.*
  3. Gerard ’t Hooft: *On the Foundations of Superstring Theory.*

(b) Philosophers of science:
  4. Dean Rickles: *Mirror Symmetry and Other Miracles in Superstring Theory.*
  5. Richard Dawid: *Theory Assessment and Final Theory Claim in String Theory.*

(c) String theorists exploring special aspects of the theory:
  6. Vijay Balasubramanian: *What we don’t know about time.*
  7. Steve Giddings: *Is string theory a theory of quantum gravity?*
  8. Steven Gubser: *The gauge-string duality and heavy ion collisions.*
  9. Emil Martinec: *Evolving Notions of Geometry in String Theory.*

(d) String theorists providing general assessments and views:
  10. Leonard Susskind: *String Theory.*
  11. Michael Duff: *String and M-theory: answering the critics.*

2 The Contributions

(a) Critics

The first three contributions are by leading non-string theorists working in alternative theories of quantum gravity: Carlo Rovelli, Lee Smolin, and Gerard ’t Hooft. Rovelli draws a personal and balanced, point-by-point comparison between string theory and loop quantum gravity. He compares the two theories on the problems of ultraviolet finiteness, quantum geometry, applications to the real world, unification, and predictions. Rovelli makes the important point that “As far as clear verifiable predictions are concerned, loop quantum gravity is in no better shape either” and stresses that “What I think is important is to keep in mind that these theories are provisional.” His point regarding string theory is a cautionary one: “Until the description of our world is found in this immense paper edifice, it seems to me that caution should be maintained.”

Smolin’s contribution concentrates on the problem of the landscape, an issue which “while it arose in string theory, is likely to be there whatever the fundamental unification of physics turns out to be”. Based on the idea of evolving laws of physics—which he traces back to Wheeler, Dirac, and Pierce—and on Leibniz’s ‘principle of sufficient reason’ as well as on what Smolin calls the ‘Newtonian paradigm’ for the structure of physical theories, Smolin develops a cogent and systematic set of requirements for any acceptable solution of the landscape problem, and applies this framework in a number of cases and alternatives, which he classifies into: pluralistic cosmological scenarios, linear cyclic scenarios, and branching scenarios.

Interesting in his contribution are the connections he draws between the landscape problem and the problem of background independence, his analysis of Leibniz's principle of sufficient reason and its connection to background independence, as well as the connection of the landscape problem as it arises in string theory to deeper issues such as the requirement that a complete scientific understanding should include understanding of the laws themselves.

't Hooft discusses the foundations of string theory and focuses on a pressing problem: the definition of string theory as a *theory*. He compares string theory to other theories and models which are not free of problems but we generally consider to be well-defined: celestial classical mechanics, quantum mechanics, and QCD, and concludes that string theory is not in as good shape as any of these theories. Despite its success in the computation of black hole microstates in special situations, using dual pictures, "What is needed is a theory that explains black hole microstates as a local property of horizons, where the Schwarzschild horizon should be the prototype". Finally, 't Hooft makes the point that string theory, just as ordinary quantum mechanics, gives rise to probability distributions rather than definite certainties. Whether one agrees with 't Hooft's view on the emergence of quantum mechanics or not, his is a case in point that, with few exceptions, string theory has so far taken quantum mechanics more or less for granted, rather than further elucidating its foundations, as one would wish for a fundamental theory. This is certainly a direction to be explored by string theory in the future.

(b) Philosophers of Science

Two philosophers of science, Dean Rickles and Richard Dawid, give their own broad assessments of the current status of string theory. They both praise string theory's mathematical success, and struggle with its lack of experimental confirmation. Nevertheless their positions are different in an interesting way. Rickles develops a version of the "no-miracles argument" for scientific realism to the case of mathematically fruitful theories, thereby defending the *rationality* of those who pursue string theory in the absence of better alternatives, rather than making a statement about the *truth* of the theory. The justification for string theory, Rickles argues, is stronger than that of a mere hypothesis: "Having a hypothesis that naturally generates a consistent and widely applicable mathematical framework ought, I argue, to increase our credence in that hypothesis". According to this view of *consilience,* string theory "scores highly overall *given the absence of a competing theory that has made a well-confirmed experimental prediction.*"

Dawid's contribution is interesting in that he develops a framework that attempts to understand what he calls "an emerging new conception of theory assessment that relies strongly on the identification of limitations to the underdetermination of scientific theory building". Dawid reviews the classical paradigm of scientific theory assessment, based on the crucial principle that theory confirmation must rely on empirical data. While acknowledging the centrality of this principle, Dawid points out that the strong focus on this aspect "marginalizes an aspect of reasoning that arguably constitutes an important element of scientific thinking: the assessment of scientific underdetermination", the degree to which no other scientific solution to the problem addressed can be foreseeably found. “Assessments of scientific underdetermination were always acknowledged as playing some role in the context of discovery but were denied any role in the context of justification. (...) [T]his understanding was never entirely satisfactory.” According to Dawid, “assessments of underdetermination are not absolutely incapable of generating scientific knowledge but merely happened to be too weak for doing so up to now.” “The emerging new paradigm moves away from an understanding, however, that attributes the status of mere hypotheses to scientific theories which have found no empirical confirmation.” Dawid provides three interdependent arguments as for how string theory limits scientific undetermination and discusses historical evidence in support of his thesis that two of his criteria appear as reliable indicators of a theory’s validity even in the absence of initial empirical confirmation in the context of fundamental physics: “predictive success tends to occur in conjunction with (i) a scarcity of known alternatives and (ii) unexpected explanatory interconnections: all three phenomena are natural consequences of limitations to scientific underdetermination.” His answer to the Darwinian argument against ‘few alternatives’ includes the statement that “scientists tend to be capable enough for finding alternative theories if such alternatives abound”. According to Dawid, “Non-empirical theory assessment breaks new ground in replacing the old dichotomy between empirical confirmation and mere speculation by a continuum of degrees of credibility”. “A sober look at the current situation in fundamental physics suggests that the old paradigm of theory assessment has lost much of its power and new strategies are already stepping in.”

(c) String Theorists Exploring Special Aspects of String Theory

Four papers by leading string theorists—Vijay Balasubramanian, Steven Giddings, Steve Gubser, and Emil Martinec—review and assess for us the status of four important aspects of string theory within the wider context of quantum gravity research. These are, respectively: (1) The problem of time, (2) String theory as a theory of quantum gravity, (3) The recent use of gauge-string duality in actual heavy ion collisions experiments, and (4) the notions of geometry and topology in string theory. Balasubramanian discusses seven deep questions that issue from careful consideration of the concept of ‘time’. These questions arise in the path integral approach to quantum field theory, in general relativity—particularly in the context of black holes—and in string theory, particularly AdS/CFT and matrix models. Then he goes on to discuss the sense in which one may, analogously to how a space-like dimension emerges in AdS/CFT, in the context of dS/CFT speak about an ‘emergent time direction’ starting with a timeless setting. He also reviews work along this direction in the context of D-branes and the large-N limit of matrix models.

In a self-critical and informative contribution, Giddings asks *Is String Theory a Theory of Quantum Gravity?* He engages in a critical review and assessment of the progress in this direction, along several fronts: the gravitational $S-$matrix in the ultraplanckian regime, the degree to which holography in general and AdS/CFT in particular provide a non-perturbative definition of the theory, and several important related issues such as unitarity, black hole complementarity, and the possibility of having nonlocal theories while retaining causality.

Gubser's contribution concentrates on heavy ion collisions and the role of gauge-string duality there. However, Gubser's article starts with a cautious praise of string theory, in which he argues that "As biting as these criticisms have been, they are (with a caveat I will come to next) attacks on a straw man." The caveat would seem to imply at least a change of perspective, if not disagreement, with Dawid's earlier quoted stance. According to Giddings, "ordinary standards *should* be applied to string theory, no matter how amazing its theoretical reach might become." In a self-reflective comment, he remarks that "Perhaps it is precisely our reticence to articulate these concerns that gives critics an opening for their straw man argument." And he concludes: "The main truth that I would draw out of the impressive statements I started with is that string theory sits at the center of a locus of ideas that spans a large fraction of modern theoretical physics"; "on one hand, it draws in the imagination; on the other, it reaches out to many other fields of theoretical physics. In an attempt to convey these qualities, I once wrote, "I think about how black holes in a fifth dimension relate to collisions of heavy ions, and people take me seriously." " Gubser gives a very nice review of how holography relates super-strings to heavy ion collisions. That includes a "new regime of simplicity [which] is fluid dynamics." "[T]he fluid that emerges is composed of strongly interacting quarks and gluons."

Martinec gives a lucid review of 'stringy geometry' which includes an account of how Einstein's equations follow from the worldsheet dynamics of the string, in particular from the condition of scale invariant string propagation. He discusses a stringy uncertainty principle, where uncertainties in distance scale are always larger than the string length, a 'minimum length' which for a long time was taken as an indication that it prevented finer distance resolution than the string length. He discusses various types of singularities in string theory and how in the context of Calabi-Yau manifolds these can sometimes be resolved in different ways, therefore admitting a change of topology between topologically distinct geometries that are smoothly connected. He emphasizes that the "topological structure of spacetime is a choice to be decided upon by the dynamics itself", in contrast to conventional notions of geometry, where "one had to decide a priori the topological data in setting up the initial conditions for dynamics and this data is fixed forever after". In a section on quantum gravity, Martinec explains that, whereas perturbative string scattering has a resolution of the order of the string length, D-branes can resolve up to the Planck scale. "Thus with the introduction of D-branes it was discovered that the fundamental scale of the theory is the Planck scale, and not the string scale." This reflects the various morphs which string theory has undergone during its various 'revolutions'. Martinec also discusses the practical implications of D-branes for their spatial locations described as non-commutative matrices. He explains how this fits in with the idea of black hole complementarity and the holographic principle, and how in restricted cases "field theories provide a non-perturbative realization of quantum gravity."

(d) String Theorists Providing General Assessments and Views

The last two contributions are from to two sting theorists—Leonard Susskind and Michael Duff—whose contributions provide general assessments and broader vista's on the future of string theory. Susskind's paper reviews the original motivation for the formulation of strings and the problems they resolved—confinement, linear Regge trajectories, and hadronization. He then explains how the presence of gravitons turned string theory into a candidate theory of quantum gravity, the problems that such a theory had to face—including the conservation of information—and the new ideas that came out of those discussions. In a section called ‘The End of Reductionism’, Susskind argues that developments in string theory are telling us that a narrow form of reductionism is wrong: “[I]f one listens carefully, string theory is telling us that in a deep way reductionism is wrong, at least beyond some point.” The reason is that various string dualities interchange what is fundamental and what is composite, large and small lengths scales, high-dimensional objects with lower-dimensional objects, and so on. According to Susskind, “In string theory this kind of ambiguity is the rule.” “Personally, I would bet that this kind of anti-reductionist behavior is true in any consistent synthesis of quantum mechanics and gravity.” Susskind also explains the implications of string theory for the issue of information loss, in particular for the question ‘where is the information?’ He closes with a discussion of the Landscape which involves another prediction: “what we can say is that if the multiverse concept proves correct, it will be an enormous success for string theory. If it proves wrong then it’s back to the drawing board.”

The last contribution to the special issue, by Michael Duff, takes issue as its title says—*String and M-Theory: Answering the Critics*—with various criticisms against string theory, from public debates, popular media and books, newspapers and magazines. Needless to say that the opinions expressed in this paper are entirely the author’s own and that it is not our intent to spark new popular or otherwise heated discussions. Nevertheless, we are happy to include this paper in our special issue as addressing questions that are important not only to scientists but also to the wider public, which was among our initial intents. It might be somewhat unusual to see newspapers and magazines quoted in a journal article on the natural sciences. However, discussions in scientific journals should not be isolated from broader societal discussions, but should reflect the two-way communication channel that exists between the scientific literature and other types of media. It is in this context that Michael’s thoughtful reply to the many criticisms that have appeared in the literature was needed in a scientific journal. We warmly recommend Duff’s very readable and playful contribution.