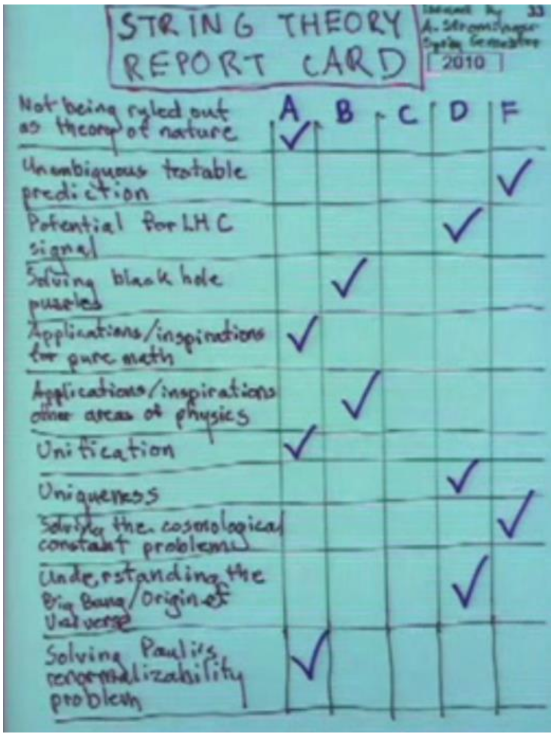
Constraints and Divergent Assessments of Fertility in Non-Empirical Physics in the History of the String Theory Controversy

To appear in Studies in History and Philosophy of Science.

1. Introduction

In a lecture on the pedagogical value of black holes, Andy Strominger closed with a brief appraisal of string theory and delivered a report card in which he awarded string theory a series of 'grades' for a list of desired attributes (see Figure 1). Of note was Strominger's declaration that the grades were uncontroversial and that any individual with some knowledge of string theory would agree, give or take a little, with each grade awarded. However, Strominger claimed that, despite this agreement over grades, individuals would disagree as to whether this report card was a pass or fail. Strominger concluded in the following way: "I would just like to comment that [string theory is] the only student in the class and if you flunk her you have to shut the school down" (Strominger, 2010).



STRING THEORY REPORT CARD

2010

	A	B	C	D	F
Not being ruled out as theory of nature	✓				
Unambiguous testable prediction					✓
Potential for LHC signal				✓	
Solving black hole puzzles		✓			
Applications/inspirations for pure math	✓				
Applications/inspirations other areas of physics		✓			
Unification	✓				
Uniqueness				✓	
Solving the cosmological constant problems					✓
Understanding the Big Bang/Origin of Universe				✓	
Solving Pauli's renormalizability problem	✓				

Figure 1 'String Theory Report Card' Source: (Strominger, 2010)

Two of the more polemical figures in the string theory debates took to their respective blogs to comment on Strominger's report card, each confirming Strominger's characterisation of the situation. It is useful to compare the comments of ardent string theory supporter Lubos Motl and critic of string theory Peter Woit side by side:

> "I think Andy is right that people would agree with the grades; they would disagree with whether it is a passing or failing report card. However, as Strominger emphasizes, string theory is the only student in the class. ;-) If you flunk her, you have to shut the school down." (Motl, 2010)

> "I think Strominger is right that his grades and point of view about string theory are now conventional wisdom among leading theorists. What I find striking about this is the argument that if you are forced to give up on string theory, you have to "shut the school down" … More than 25 years of working on string theory has left Strominger and others somehow believing that there is no conceivable alternative … The obvious conclusion that string theory is just one speculative idea, and that its failure just means you have to try others, is one that they still do not seem willing to face up to." (Woit, 2010)

Here Motl affirms Strominger's assessment that string theory is currently the only viable approach which justifies future work, whereas Woit argues against exclusively pursuing string theory (at the expense of developing alternate approaches) in quantum gravity research. Not only is the commentary a striking confirmation of Strominger's characterisation of his appraisal of string theory, it also highlights two aspects of the debates over string theory: that there is agreement as to the relevant categories for assessment of string theory, as well as the assessment of the particular characteristics of string theory; and that, despite this, there is disagreement concerning the viability of string theory.

In this paper I will analyse historic examples from the string theory debates as examples of assessment, with the aim of developing an historically informed understanding of the string theory controversy and assessment in non-empirical physics. The string theory controversy is sometimes held up as evidence of the emergence of a non-empirical methodology in high energy physics, and of a 'meta-paradigmatic rift' (Dawid, 2009) between competing empirical and non-empirical methods. In this paper I show that a detailed historical approach to investigating this claim reveals that there are a number of points of conflict in the controversy. One of these points of conflict is indeed the famous controversy concerning whether non-empirical methodology constitutes science (Ritson & Camilleri 2015; Ritson, 2016). However, this paper will focus on other aspects of the string theory debates which rested on considerations of constraints and divergent claims concerning the fertility of non-empirical theoretical content.

The paper proceeds as follows. By way of introduction to constraints, section two outlines the role of renormalisability – an undisputed constraint. Section three examines in turn a number of constraints: consistency, background independence, non-perturbative formulation, and applications, where there is both agreement as to the current status of string theory and commitment to each constraint, and where the disputes are located in the role of each constraint in theory construction and appraisal. In this section of the paper, the historical examples detail those divided in their assessments of whether string theory is the most promising approach to constructing a (unified) quantum theory of gravity. There is a great deal of diversity in the arguments presented; however there is a broad, and unsurprising, trend that those with a positive assessment of the promise of string theory (such as Andrew Strominger, Joseph Polchinski, Brian Greene, John Schwarz, and Michael Duff) are those who worked on string theory in some capacity. By contrast, those who dispute the promise of string theory (such as Lee Smolin, Peter Woit, Gerard 't Hooft, John Baez, and Carlo Rovelli) have not (with the exception of Smolin who did initially work on string theory). Section four examines the debates over the legitimacy of anthropic reasoning and the necessity of uniqueness and, in contrast to section three, I argue that the debate centres on commitment to or abandonment of constraints. In these debates, even the string theory community has historically divided.

2. Constraints

Considerations of the role of methodological virtues in the historical development of theories of quantum gravity can be found in Rickles (2011). Rickles argues that the methodological virtues that guide research in quantum gravity have not been empirically based and yet the history of quantum gravity is full of failed theories, asking “if not the standard methodological virtues, what is guiding theory constructions and selection is this case?” (Rickles, 2011, p. 4). Rickles argues that it is useful to draw upon Galison’s notion of constraints (Galison, 1995). For Galison, constraints play a role in shaping a research program: “To a large extent, and across many domains of science, constraints are constitutive of the positive research program. They create a problem domain, giving it shape, structure, and direction” (Galison, 1995a, p. 22). Rickles’ observation is that in the history of attempts of quantum gravity, in the absence of experiments and observation, it must be constraints that are guiding theory construction and selection (and rejection) (2011b, p. 35).

Both Rickles and Galison draw on a quotation from Weinberg in their discussion of constraints:

> “[I]t seemed to me to be a wonderful thing that very few quantum field theories are renormalizable. Limitations of this sort are, after all, what we most want; not mathematical methods which can make sense out of an infinite variety of physically irrelevant theories, but methods which carry constraints, because these constraints may point the way towards the one true theory. In particular, I was very impressed by the fact that [Quantum Electrodynamics] could in a sense be derived from symmetry principles and the constraint of renormalizability; the only Lorentz invariant and gauge invariant renormalizable Lagrangian for photons and electrons is precisely the original Dirac Lagrangian”. (Weinberg, 1980, p. 517) quoted in (Galison, 1995, p. 22) and (Rickles, 2011, p. 36)

For Galison, this quotation is taken as evidence for the “tremendous positive role of the theoretical constraint in defining the field of inquiry” (Galison, 1995, p. 22). Rickles examines the particular role of renormalisability in string theory, arguing that, within the context of a history of failed attempts at developing a renormalisable theory of quantum gravity, the role played by the constraint was positive appraisal: “string theory was given credence because it offered the prospect of a finite theory” (Rickles, 2011, p. 36). Both Rickles[1] and Galison historically situate constraints; for Galison, the primary historical-philosophical questions are “how do these constraints arise, what sustains them, how do they act, and what makes them fall?” (Galison, 1995, p. 14) In this paper I will show that constraints do act so as to structure non-empirical appraisal. A structure based on common reference points such that those in the debates over string theory can rationally debate and appraise string

---

[1] Rickles has a detailed description of the role of a variety of constraints in various theories of quantum gravity in *Quantum Gravity a Primer for Philosophers* (Rickles, 2008).

theory. I argue that the role of constraints is to regulate assessments of past and future fertility; and to facilitate rational debate of string theory as a theory of quantum gravity.

3. Undisputed constraints in the string controversy

3.1 Consistency

Consistency is a powerful constraint in quantum gravity research. The problem of quantum gravity can be considered to be a consistency problem whereby current understanding is deficient (in that general relativity is inconsistent with quantum field theory). It is difficult to overstate the credence given to consistency constraints; as such it is unsurprising that the claim that string theory is a consistent theory of quantum gravity is an oft cited argument in support, or in defence, of string theory. As Tong argues in his introduction to string theory (written for graduate students):

> "Our current understanding of physics, embodied in the standard model, is valid up to energy scales of 103 GeV. This is 15 orders of magnitude away from the Planck scale. Why do we think the time is now ripe to tackle quantum gravity? Surely we are like the ancient Greeks arguing about atomism. Why on earth do we believe that we've developed the right tools to even address the question? … the most compelling argument for studying physics at the Planck scale is that string theory does provide a consistent unified quantum theory of gravity and the other forces." (Tong, 2012, p. 8)

That theories should be constrained by consistency is not a controversial claim, as inconsistency has the potential to render a theory non-physical[2]. The controversy over consistency in string theory refers to sufficiency of consistency to constrain a theory such that it will pick out the theory of quantum gravity that describes our universe. Alternatively, it is argued that consistency is sufficient to constrain the process of theory construction such that future progress will occur.

3.1.1 Arguments for the sufficiency of consistency

In the face of the experimental difficulties of *any* theory of quantum gravity, some argue that theoretical criteria will lead them to a solution to the problem of quantum gravity. Utilising an argument of an inference to best explanation, theorists such as Weinberg claim that consistency and rigidity are sufficiently constraining such that any theory that held these properties had to be saying something about the our universe; "[string theory] has the kind of rigidity that you look for in a kind of physical theory that will in the end turn out to have something to do with the real world" (Weinberg quoted in (Galison, 1995, p. 386)). Weinberg argues that such a theory will be "logically isolated" because any slight change would destroy the internal consistency of the theory, and that "we would know on the basis of pure mathematics and logic why the truth is not slightly different" (Weinberg, 1993, pp. 236-

---

[2] Although, non-physical does not necessarily imply non-useful; a famous example being the Bohr model of the atom.

237). Schwarz has also argued along these lines: “I believe that we have found the unique mathematical structure that consistently combines quantum mechanics and general relativity. So it must almost certainly be correct” (Schwarz, 1998, p. 2). Schwarz’s claim here draws upon internal, or mathematical, consistency and also external consistency, consistency with existing well-established theories. Greene has also argued that this “unification utopia”, or a combination of internal and external consistency (Greene, 1999, p. 183), “would declare that things are the way they are because they have to be that way” (Greene, 1999, p. 283). Here the combination of internal theoretical consistency, rigidity, and external consistency is argued to have the potential to be sufficient to guide assessments of the veridicality of theories of quantum gravity (see section 3.2 for further discussion of ‘external consistency’).

Rather than arguing that consistency may be sufficient to determine the ‘true’ theory of quantum gravity, Susskind has argued that consistency may be sufficient to determine that progress has occurred, and is likely to continue in the future, in quantum gravity research:

> “String theory has had a profound, and I believe lasting, influence on how gravity and quantum mechanics fit together. In order to illuminate the conceptual problems of quantum gravity it may not be important to discuss the precise form of the theory that describes our corner of the universe. What may be more important is to know what is, and what is not consistent; what kinds of things are possible; what kinds of structures to expect. One should not underestimate the importance of having a mathematically consistent structure that contains both quantum mechanics and gravity” (Susskind, 2013, p. 176).

Susskind avoids making the strong claim that consistency (both external and internal) should inform ontological commitments. Instead, he argues here that consistency is epistemically important in that it has in past provided a guide to knowledge of the problem of quantum gravity, and in that in his assessment it will continue to guide knowledge of the problem, and potential solution, of quantum gravity. That is to say, he argues that the combination of internal and external consistency may be sufficient to inform an assessment of the past fertility of string theory and for assessments of string theory’s potential for future contributions to quantum gravity.

3.1.2 Arguments against the sufficiency of consistency

Rovelli, who played a significant role in the development of a rival theory of quantum gravity, Loop Quantum Gravity (LQG), has argued against the sufficiency of consistency. Rather than opposing consistency as a constraint in his criticisms of string theory, Rovelli offers a series of criteria by which the success or failure of string theory (and LQG) may be judged: “completeness, internal consistency, full agreement with known low-energy physics, simplicity, and, ultimately, experience, will tell” (2013, p. 19). Rovelli argues that consistency is necessary but not sufficient.

Rickles has also argued that historically in quantum gravity research consistency has been compelling in convincing theorists to pursue particular theories. However, Rickles argues against the sufficiency of consistency arguments to determine uniquely a theory of quantum gravity: “[internal consistency and external compatibility] do not appear to be sufficiently stringent to uniquely determine the desired theory of quantum gravity; instead there are multiple research avenues that each seem to satisfy the constraints” (Rickles, 2008a, p. 264). Similarly, Feynman also noted that in the historical development of Quantum Electrodynamics internal consistency, the removal of infinities, played a significant role. However, he also argued: “I don’t think that the statement that theories cannot have any infinites leads us uniquely to this string theory … The fact that a theory gets rids of the infinites is to *me* not a sufficient reason for believing in its uniqueness (Feynman, quoted in Davies & Brown, 1988, p.197-200, emphasis author’s own). Both Rickles and Feynman invoke uniqueness in the sense of ‘to the exclusion of all others’ to argue that internal consistency is not sufficient to inform a selective assessment of an approach to a unified theory of quantum gravity.

3.2 Background independence

Background independence refers to a property of relativistic theories in which the spacetime metric can be obtained as a solution of the dynamical field equation. General relativity is regarded as a ‘background independent’ theory in this sense, because the field equations can be formulated without reference to any particular spacetime coordinate system. Just as with the constraint of internal consistency, physicists generally agree that a quantum theory of gravity should be background independent. However, they disagree about exactly how we should interpret this constraint on theories of quantum gravity. Beyond an intuitive notion, there is no agreed technical definition of ‘background independence’ (Pooley, 2017 & Rickles, 2008b).

There is a sense in which the constraint of background independence may be understood under the umbrella term of ‘external consistency’. External consistency is where a theory of quantum gravity is expected to be consistent with existing well-established theories. In this case the constraint of background independence may be interpreted as an expectation that a theory of quantum gravity must be compatible with general relativity. In 2001 ’t Hooft argued for a “physics without experiments” and provided a list of constraints (in his words, “tests of the following kinds” (’t Hooft, 2001, p. 2898)) for building theories without experiment. The third in that list was that theories “should agree with older theories that are well-established. Thus, most advanced particle theories such as string theory, M theory and the like are demanded to agree at least with quantum mechanics, and special and general relativity” (’t Hooft, 2001, p. 2898). This broad commitment to external consistency, or a correspondence principle, is not considered to be problematic: as a generalised expression it is unlikely that the constraint will generate dispute. Difficulties arise in particular cases in understanding how the constraint should guide theory construction and evaluation. In what follows it becomes clear that what is disputed is not whether theories should be constrained by background independence but how to evaluate whether the constraint has been met, as well as the significance of the constraint.

Smolin identified background independence as among the most significant of constraints in developing a theory of quantum gravity:

> "String theory is not currently formulated as a background-independent theory. This is its chief weakness as a candidate for a quantum theory of gravity. We understand string theory in terms of strings and other objects moving on fixed classical background geometries of space that don't evolve in time. So Einstein's discovery that the geometry of space and time is dynamical has not been incorporated into string theory." (Smolin, 2006, p. 184)

In his response to Smolin, Polchinski argued that Smolin had not understood the way in which background independence should constrain methods of theory construction:

> "[Smolin] is mistaking an aspect of the mathematical language being used for one of the physics being described. New physical theories are often discovered using a mathematical language that is not the most suitable for them. This mismatch is not surprising, because one is trying to express something that is different from anything in previous experience." (Polchinski, 2006)

It is evident that for Polchinski, just as for Smolin, in the process of theory construction the methodology should be constrained by background independence. Where they differ is in their appraisal of the capacity of string theory to meet the constraint satisfactorily. Polchinski continues: "In string theory it has always been clear that the physics is background-independent even if the language being used is not, and the search for a more suitable language continues" (Polchinski, 2006). Polchinski is suggesting a split between the representation of string theory and how string theory is understood. On the basis of this split, Polchinski advocates for theory construction to progress by developing a new form of representation. As Polchinski points out, this method of theory construction is not new: theorists build theories with the best available tools, or mathematical formalisms, and proceed by a manner of hunches and intuitions developing better tools over time.

Polchinski's account of the process of theory construction, where the representation of the physics approaches the intuition or understanding that the theorist has over time, is contradicted by Rovelli. In 2001 Rovelli argued that the historical insights provided by the introduction of no absolute motion as part of the ontology of general relativity should be considered to be instructive. As such Rovelli criticises the path followed by perturbative string theory (and the approach that Polchinski would outline years later), as in his view it does not follow the insight provided by general relativity. He argues that "right way to go" is to attempt to formulate a background independent theory from the outset rather than "hope" to recover general relativity "down the road" (Rovelli, 2001, pp. 105-109). Rovelli later extended this argument, claiming that the issue is that background independence is "not yet properly understood" by string theorists (Rovelli, 2013, p. 12). The problem, for Rovelli, is: "in all these cases, instead of addressing the real problem, which is to learn how to do physics where background spacetime plays no role, the strategy is to try to circumvent the problem" (Rovelli, 2013, p. 12). Unsurprisingly Rovelli argues that the strategy employed by LQG is superior, as the problem is addressed "upfront", resulting in a "conceptually clear, fully general relativistic, and well defined" picture of quantum gravity (Rovelli, 2013, p. 13). Here I would argue that Rovelli attempts to shift the discussion from assessments of future to past fertility: "Let's not talk about hopes, let's talk about achievements" (Rovelli, 2003, p. 1512).

3.3 Non-perturbative formulation

Closely related to the debate over background independence is the debate over a non-perturbative formulation of string theory. String theorists argue that while perturbative string theory is background dependent, there are good reasons to believe that the non-perturbative formulation of string theory is background independent. Perturbative string theory is, strictly speaking, not a theory in its own right, but rather a background dependent method that allows quantitative calculations of certain aspects of the theory. The difficulty, as both string theorists and critics point out, is that the dynamical equations of this fully formulated (non-perturbative) theory "are so complicated that no one knows their exact form" (Greene, 1999, p. 285). Polchinski and others point to dynamical features, such as topology change of perturbative string theories, which would seem to indicate that a non-perturbative formulation is background independent (Polchinski, 2006). Prospects for a fully non-perturbative formulation of string theory began to improve during a period of time labelled the 'second string revolution' in the late-1990s, with a deeper understanding of the dualities that relate the five known perturbative string theories (Polchinski, 2004). The AdS/CFT duality, first proposed by Jan Maldacena in 1997, provided physicists with what is believed to be a fully non-perturbative definition of string theory in anti-de Sitter spacetime (Maldacena, 1997).

Crucially for some, such as Smolin and 't Hooft, the duality relations (in particular the AdS/CFT duality) are yet to be convincingly proven. For Smolin: "there is evidence to support something like the Maldacena conjecture [Ads/CFT duality], but no proof of the full conjecture itself, and only the full conjecture will allow us to assert the existence of a good quantum theory of gravity" (Smolin, 2006, p. 191). 't Hooft criticises perturbative string theory for "not defining a theory" ('t Hooft, 2013, p. 50). While the duality relationships are identified as 'artillery' against the lack of a non-perturbative formulation of string theory, ultimately 't Hooft finds the strength of this 'artillery' inadequate where the string theories lack "rigorous foundation" ('t Hooft, 2013, p. 50). Here the disagreement rests on the extent to which the duality relations may be considered to support a belief in the existence of a non-perturbative formulation of string theory.

Polchinski has challenged Smolin's negative appraisal of string theory, claiming that Smolin is dependent on an overly demanding interpretation of methodology:

> "Physicists work by calculation, physical reasoning, modelling and cross-checking more than by proof, and what they can understand is generally much greater than what can be rigorously demonstrated … Physicists by their methods can obtain new results whose mathematical underpinning is not obvious. String theorists have a strong sense that they are discovering something, not inventing it." (Polchinski, 2006)

Rather than challenging Smolin's description of the duality relations as incorrect or misunderstood, or for the ultimate sufficiency of perturbative formulations, Polchinski disputed that the sceptical position adopted in response was justified when contextualised against broader methodological considerations.

It seems trivial to reduce these debates to those that are 'optimistic versus pessimistic' where the very issue of scientific judgement is at stake. Indeed, this is not the intention as the issue runs deeper than the question of whether string theory is pursuit-worthy, as not even the strongest of critics would claim that string theory is not in some sense pursuit-worthy or that all work on string theory should cease. Recalling the introduction, Woit argued for a greater diversity of approaches rather than for 'shutting the school down'.

There is a noncontroversial sense in which many scientists make many non-empirical appraisals of theory. These decisions range from very high level, choosing a speculative theoretical approach to develop, to more day to day decisions concerning choosing an experimental set up. The scientist will have some measure of confidence in the results, as is evidenced by their investment of time and resources (a particular concern for experimental physics), and this confidence cannot come from the yet to be obtained results. This confidence is not that the results will be 'correct' or provide confirmation; instead it is confidence in the fertility of the choices made. Indeed, a disconfirmation may be considered more valuable for theory construction (Ritson, 2019). What the string debates make clear is how non-empirical appraisal can be informed by considerations of both past and future fertility with respect to a number of agreed constraints within a research field. The functionality of the constraints also helps us understand how the debates go beyond optimism versus pessimism.

3.4 Applicability

One element of appraisals of string theory, often unappreciated, is an understanding of the different views concerning the non-empirical utility of string theory. For the most part, the philosophical literature on string theory has focused on string theory as a(n attempt at, or a candidate) theory of quantum gravity. However, this focus has obscured another important dimension to appraisals of string theory in terms of the scope of the utility of string theory. In addition to the view of string theory as a candidate unified theory of quantum gravity, there is also the view that string theory is a collection of methodologies and techniques that has wide applicability for solving previously intractable problems. On this view string theory is a tool that has utility in other areas of physics and mathematics such as low temperature super conductivity and quark gluon plasma calculations. The tool view of string theory can primarily be distinguished by its aim. The aim of string theory as a tool is to apply methodological techniques of string theory to other areas of physics. This is distinct from the aim to solve the problem of quantum gravity with unification.

If we return to Strominger's report card (Figure 1), we can see that Strominger awarded string theory high grades in two sections devoted to applications: an A for inspiration for pure mathematics and a B for inspiration for other areas of physics (Strominger, 2010). Again, recalling the introduction, where two of the most polemical figures in the debates over string theory both agreed that Strominger was correct in his assertion that very few would disagree with the grades awarded (Motl, 2010; Woit, 2010), we again see that there is widespread agreement in positive assessments of string theory as a tool. Earlier, Woit had also written in praise of the wider applications of string theory: "While supersymmetry and string theory have been remarkably unsuccessful so far in explaining anything about physics, they have led to a great deal of new and very healthy interaction between the fields of mathematics and physics" (Woit, 2006, p. 193).

Despite the apparent agreement of the broad utility of string theory, there remains disagreement as to how the relationship between the different aims for string theory should be understood. This relationship is argued by some to be an evidential relationship, where the successes of string theory as a tool are argued to be evidence for string theory as a unified theory of quantum gravity.

The provocatively titled 'Is String Theory a Theory of Quantum Gravity?', from string theorist Steven B Giddings, arguably offered the contribution to the *Foundations of Physics* special issue most critical of string theory (Giddings, 2013). Giddings argued that

> "string theory has been a continuous source of new ideas in mathematics and physics, and showed a lot of initial promise for resolving the problems of quantum gravity. However, the more profound problems are yet to be convincingly addressed, and there are deep puzzles about how they might be addressed by string theory" (2013, p. 135).

The ambiguity in determining levels of criticism comes from a lack of consensus as to what amounts to a critique of string theory. For those who pursue string theory exclusively as a useful set of techniques for problem solving, it is not a criticism to deny that string theory is a candidate theory of quantum gravity. For those who see developing a theory of quantum gravity that unifies the fundamental interactions as the primary goal of string theory, questioning whether string theory is a theory of quantum gravity amounts to a serious critique.

It is difficult to pin down the exact nature of the appraisals of string theory based on the relationship between string theory as a tool and as a theory of quantum gravity, partially because the appraisals are not static; instead, they evolve in an almost Bayesian way. There are two parts to the appraisals: the current status of the string theory research program and a projective assessment of the likelihood of future success. With each development, the measure of confidence of future successes of string theory updates. As such, many of the arguments are with regards to evidence that string theory is the most promising approach and much of the language is couched in terms of being "on the right track" (Bergman, 2006b; Witten, 2005, p. 1085) or "the right and possibly final track" (Greene, 1999, p. 20), and as Dawid has argued in a positive assessment: "it would look like a miracle if all these instances of delicate coherence arose in the context of a principle that was entirely misguided" (Dawid, 2013b, p. 89).

Quantum field theorist Matt Strassler and Woit had an, at times, furious debate about the relationship between string theory as a tool and as a theory of quantum gravity (see comments on (Strassler, 2013a)). Woit accused Strassler of misleading the public by claiming that progress coming from the use of string theory as a tool is indicative of progress in string theory as a theory of quantum gravity (which Woit calls string unification). For Woit, the applications of string theory are tests of an "approximation scheme" as opposed to tests of a theory (Woit, comment on Strassler, 2013a). In the second follow up post, Strassler argued that Woit had left unexplained "why string theory could be such a helpful tool for a quantum field theorist like me" and that "[b]y studying imaginary particles and forces, we gain insight into the real world" (Strassler, 2013b).

In 2015 Sabine Hossenfelder asked Clifford Johnson if there were any string theorists still working on string theory as a unified theory of quantum gravity (Hossenfelder, comment on Johnson, 2015). Johnson responded with a detailed explanation which is worth quoting as length so as to examine in detail the many facets of the arguments between the different views of string theory:

> "There is a very diverse set of topics within the subject that (along with topics like applications to condensed matter and nuclear topics) are all vital explorations of what string/M-theory really is, and what it can teach us about quantum field theory, spacetime, etc. It was clear to me (and I imagine, others) a very long time ago that it was very premature to have the entire field all working on trying to squeeze the theory into one simple ('theory of everything') role, and that we needed to diversify and explore it in many contexts (especially connecting with other types of experimental physics) in order to really get to grips with what we've got, and what the theory can and can't do. The benefits are that we (1) Get insights and useful tools for all those different corners of exploration, and (2) We strengthen the program of developing the subject for its application to the (naive, in my view) "theory of everything" quest." (Johnson, 2015)

Rather than arguing that the diverse applications of string theory are indicators of a 'grand unified theory', Johnson argues that the field is in a healthy state and as such progress is being made. Progress for Johnson is constituted by assessments of the utility of applying string theory methodologies to areas such as quantum field theory. Crucially, Johnson also argues that in applying string theory methodologies there also insights gained into string theory as a theory of quantum gravity. Earlier he argued:

> "We do not know whether any of these things have anything to do with our world…. that successful quantum gravity conceivably might not turn out to be *our* quantum gravity for example…. but as a list of things where significant progress has been made in so many theoretical physics topics by a single framework … this is why it is regarded as "promising"." (Johnson, comment on Johnson, 2006)

Johnson is careful not to argue that the progress occurring in 'tool' string theory is evidence for the veridicality of string theory. Rather, he argues that the successes in 'tool' string theory are deeply connected to string theory as a theory of quantum gravity and inform assessments of the future potential of string theory to contribute to quantum gravity research.

In contrast to the position offered by Johnson, Rovelli provides an alternate explanation of the wide application of string methodologies:

> "string theory techniques may have potential applications to other domains of physics. These are very interesting, but in no way they testify in favor of the relevance of string theory for the fundamental interactions. Enormous intellectual investments have gone into string theory in the last decades and it would be strange if all the theoretical technology developed did not turn out to be good for something." (Rovelli, 2013, p. 17)

For Rovelli, the methodological successes of 'tool' string theory do not constitute evidence for string theory as offering significant contributions to attempts at a unified theory. Camilleri and Ritson have argued that "while the debate appears on the surface to be about justification and epistemic appraisal, much of the disagreement actually concerns heuristic appraisal" (Camilleri & Ritson, 2015, p. 45). Here Rovelli argues for the future potential of string theory as a tool, and denies that this positive heuristic appraisal has any bearing on assessments of string theory as a unified theory.

One result along similar lines that deserves closer attention is the derivation of black hole entropy. The dispute over the significance of the result is such that it is difficult to locate or diagnose appraisal as appraisal of string theory as a tool or as a theory of quantum gravity.

3.3.1 Derivation of black hole entropy

In 1996 Strominger and Vafa published a landmark paper titled 'Microscopic origin of the Bekenstein-Hawking entropy' (1996). This development was considered a key element of the increase in ‘optimism’ among string theorists that characterised the so-called ‘second superstring revolution’. In the case of the work done by Strominger and Vafa, the ‘optimism’ was a result of a long-standing expectation that a theory of quantum gravity should allow for calculation of the entropy of a black hole[3] (Bekenstein, 1973 & Hawking, 1974, 1975). Strominger and Vafa showed that for extremal five-dimensional black holes the quantum microstates could be counted by hand in agreement with the Bekenstein-Hawking area law. The choice of language to describe these historic developments is difficult as it has been contested by some, such as Baez and Eric Curiel who both expressed criticism of the descriptions of the class of black holes utilised in the calculation (Baez, comment on Bergman, 2006a; Curiel 2001). Much of this disagreement comes from differing interpretations of the significance of the calculation in the case where the black holes are unphysical.

There are many testimonials as to the significance of the development. Duff argued that:

> “String and M-theory continue to make remarkable theoretical progress, for example by providing the first microscopic derivation of the black hole entropy formula first proposed by Hawking in the mid-1970s. Solving long outstanding theoretical problems such as this indicates that we are on the right track.” (Duff, 2013, p. 184)

There are two potential interpretations of Duff’s ‘on the right track’ here. One is that string and M-theory is getting closer to the goal of offering a solution to the problem of quantum gravity. A second interpretation is that solving problems is, for Duff, considered to be evidence for string and M-theory as a method. Both interpretations are consistent with Duff’s position: Duff is arguing that the calculation is evidence for both string theory as a tool and as a unified theory of quantum gravity, and as evidence for the future potential of both the theory and the methods.

Aaron Bergman has argued that the derivation is also evidence for string theory as a theory of quantum gravity. He argues that:

> “This is a striking confirmation that, for whatever its other flaws, string theory really is *a* theory of quantum gravity … The significance of this is that, even if string theory turns out to be the wrong theory of quantum gravity, how it solves the puzzles presented by the unification of quantum mechanics and gravity will aid us in understanding and formulating future theories.” (Bergman, 2006b, p. 10)

---

[3] In 1974, drawing on the earlier work of Bekenstein, Hawking predicted that black holes radiate energy. The amount of energy radiated would be proportional to the gravitational ‘temperature’ which is also proportional to the mass, angular momentum, and charge of the black hole. The expectation for a theory of quantum gravity is that it would allow a calculation of the entropy of a black hole of given mass, angular momentum, and charge where the entropy corresponds to the number of quantum microstates of the gravitational field having the same mass, charge, and angular momentum. Curiel has been critical of this ‘test’ of a theory of quantum gravity as the predicted radiation has not yet been observed; as such Curiel denies that the successful calculation performed by Strominger and Vafa secures the scientific status of string theory (Curiel, 2001).

Rather than being evidence that string theory, as understood in 2006, was the correct theory of quantum gravity, Bergman instead argued that the methodology for the successful calculation of black hole entropy for extremal black holes (the "*how* it was calculated" as opposed to the calculation) is instructive for understanding quantum gravity.

Rovelli, whilst agreeing that the calculation is a success for string theory, disagreed as to the calculation's significance. Rovelli argued that the derivation is insufficient to differentiate between the two rival approaches, string theory and LQG (as LQG can also claim a partial success[4]). Furthermore, for Rovelli, it is at best a "partial" success and he remains unconvinced that a full solution is forthcoming for string theory:

> "The string derivation is still confined to, or around, extreme situations, as far as I know, and since it is based on mapping the physical black-hole solution into a different solution, it fails to give us a direct-hand concrete understanding of the relevant black hole degrees of freedom, as far as I can see." (Rovelli, 2013, p. 16)

For Rovelli, the calculation is a successful application of string theory and not sufficient evidence for string theory to be considered the most promising approach in quantum gravity research.

Where Bergman and Duff saw evidence for a successful methodology, Rovelli saw a methodology couched in avoidance, that rather than solving the problem "the strategy is to try to circumvent the problem" (Rovelli, 2013, p. 12). Along similar lines, 't Hooft also criticised the methodology as likely to deter progress:

> "[String theorists] appear to prefer to discover more and more new "stringy miracles", such as new miraculous matches of black hole microstates, or new cosmological scenarios. If any logical jumps appear to be too large to comprehend, we call these "conjectures", find tests to corroborate the conjectures, and continue our way. These are easier ways to score successes but only deepen and widen the logical depths that block any true understanding." ('t Hooft, 2013, p. 47)

There is of course a long history in physics of using toy models for calculating complex and difficult scenarios. The difficulty in the case of assembling and assessing a candidate theory of quantum gravity, where experiment is unlikely to provide evidence, is in how to asses and interpret theoretical achievements as evidence for a theory or a methodology, and to what extent these achievements should inform appraisals of the future fertility of methods and theories. It is here worth reflecting on the notion

---

[4] LQG can be used to build a model of semiclassical black holes, including recovering the expected results of the Bekenstein-Hawking law. For a comparison of string theory and LQG concerning black hole thermodynmics see Barbero (2011)

of fertility, in order to gain further insight into the divergent assessments of past and future fertility in the debates over constraints in the string controversy.

3.5 Constraints and Divergent Assessments of Fertility

McMullin (1977) focused on fertility for realist accounts of confirmation (as an alternative to novel predictive successes, given the potential for an ad hoc theory that makes novel predictions). McMullin drew a distinction between ‘proven’ and ‘untested’ fertility where “[t]o estimate the P-fertility of a theory, one has to retrace its career and see how successful it has been in suggesting the right modification at the right time and in allowing incorporation of new areas not originally foreseen” (p. 400-401). By contrast ‘U-fertility’ is a “future oriented affair”, “the potential of a theory for further (as yet untested) development” (p.401). Appraisal of U-fertility, according to McMullin, focuses on “what is its research-potential for the future? how likely is it to give rise to interesting extensions? Does it show promise of being able to handle the outstanding problems (inconsistencies, anomalies, etc.) in the field? Is it likely to unify hitherto diverse areas, or perhaps open up entirely new territory?” (1976, p 423-424). Nolan (1999) later argued that the value of U-fertility is that a theory or research programme is “valuable as a means rather than an end” as a ‘U-fertile’ theory “may contain in it the ‘seeds’ of a theory which gives a description of several apparently disparate phenomena in terms of the same underlying theoretical resources, this offering the potential of greater theoretical unification” (p. 270-271). Nolan and McMullin point to something important concerning the practices of appraisal for scientists, who are more often dedicated to evolving work than to assessments of past work.

Both McMullin’s distinction between P- and U-fertility and Nolan’s clarification as to the value of U-fertility are of use here in further explicating the notions of past and future fertility found in the historic examples of assessment in the debates over string theory. However, a small modification is required: non-empirical assessments of past fertility are not necessarily assessed as ‘proven’, as was especially clear in the contested assessments in the debates over background independence and a non-perturbative formulation of string theory. Instead, these assessments are not of static achievements: they are situated in the context of the evolving developments of string theory. Claims as to the fertility of the string theory research program concern whether it has successfully guided research, and if it has the potential to continue to guide future research in quantum gravity, whether string theory has both been and will be “valuable as a means rather than an end” (Nolan, 1999, p. 270). Nolan points us to a crucial aspect of non-empirical assessment in the history of the string theory debates: non-empirical assessment proceeds as assessment of string theory as means, rather than end.

Whilst McMullin’s distinction, modified here, nicely captures the nature of non-empirical assessment in the string theory debates, it is also important to consider what guides such assessments of the past and future fertility of theories of quantum gravity. What is argued here is that it is the function of constraints to regulate assessments of the past and future fertility of string theory.

Elgin has also argued that for individual epistemic agents, aesthetic factors (such as symmetry and elegance) can play a regulatory role as "gatekeepers" (Elgin, 2020, p 35). Whilst Elgin's focus is on how aesthetic factors can contribute to understanding, her account offers insight into the function of constraints in this case study. Elgin argues that the role of aesthetic factors is to introduce optional stops, as deviations from expectations generated from aesthetic factors require explanation. Which is to say that if an epistemic agent perceives a deviation from their aesthetic ideals, such as symmetry or elegance, they will stop on the basis that this deviation is a problem that needs to be solved for coherence.

In the history of the string theory debates, the function of constraints is also regulative. However, whilst it would almost certainly be the case that deviations from constraints would require explanation (as will be discussed in the next section), instead of introducing optional stopping points assessments are iterative and evolve. Constraints do establish expectations for the epistemic community, but they are, unsurprisingly, not severe or precise tests. It is not enough to simply argue that string theory is, for example, internally consistent, thereby passing by an optional stop. In each of the constraints discussed thus far, there is agreement for the relevance of the constraint but yet there is still debate as to appraisals of the future fertility of string theory. For example, the cluster of arguments concerning consistency in the debates concerns the sufficiency of internal and external consistency for assessments of the future fertility of string theory. There is agreement both as to the significance of internal and external consistency, but disagreement as to whether consistency is sufficient for an appraisal of string theory as the only fertile path to a unified theory of quantum gravity. Rather than a problem to be solved, constraints function as common reference points in the divergent assessments of string theory and give structure to the debates. Constraints positively define the problem space.

Thus far in this paper I have shown how assessments of the fertility of string theory evolve with reference to uncontroversial constraints. Debate and controversy arose over determinations of string theory as a means, on the future fertility of string theory, with the divergent assessments each based upon the same constraints. As such I have thus far examined the role of constraints for those divided in their assessments of the fertility of string theory; in the next section those in agreement as to the fertility of string theory are themselves divided.

4. Disputed constraints in the string controversy

In this section, I will identify points of conflict within the string theory community as to the virtue of anthropic reasoning and uniqueness. These two contested constraints are intimately connected, as both are concerned with the landscape scenario and as such are often conflated. However, the following will argue that there are two, sufficiently distinct disputes occurring and that there is value in exploring each separately. There is now a burgeoning literature in the philosophy of cosmology dedicated to issues concerning the multiverse interpretations of the landscape[5]. This paper will focus only on the historic debates internal to the string theory community with regards to the legitimacy and utility of anthropic reasoning and the necessity of uniqueness.

4.1 Uniqueness and the landscape problem/solution

In 2003 the string theory community began to discuss the multiverse scenario, where it was believed that there was a large number of consistent string theories (on the basis of the landscape of 10^{500} or more metastable low energy vacua). The multiverse scenario led some to question whether it is possible, in principle, to develop testable predictions for string theory (Ritson and Camilleri 2015). Here I will examine a further point of contention concerning whether theories of quantum gravity should be constrained by uniqueness. The controversy over the necessity of uniqueness in string theory, while not previously absent, was certainly heightened following 2003. Drawing on what is known as the KKLT paper (Kachru et al., 2003) and from Buosso and Polchinski (2000), in 2003 Susskind published his lecture from The Davis Meeting On Cosmic Inflation, 'The Anthropic Landscape of String Theory' (Susskind, 2003). Susskind argued for the legitimacy of anthropic reasoning (which will be discussed in the following section) as well as for the rejection of uniqueness as a constraint. Susskind's proposal was a controversial one and was greeted with hostility, not only by some critics of string theory but also by many in the string community who viewed the rejection of uniqueness as a rejection of a long term aim of string theory, quantum gravity, and physics.

4.1.1 The necessity of uniqueness

Uniqueness was an uncontroversial constraint on string theory for almost three decades. So uncontroversial that often no argument was offered in the debates for the necessity of uniqueness. Greene claimed that uniqueness was paramount: "the ultimate theory should take the form that it does because it is the unique explanatory framework capable of describing the universe" (Greene, 1999, p. 283). Other claims would refer to historic successes of unification attempts constrained by uniqueness. This view represents what Kragh described as the "Einsteinian ideal" where the construction of an unique unified theory was considered to be a continuation of the work of Einstein (Kragh, 2011, p. 214).

A second significant figure in the debates over uniqueness is Geoffrey Chew, who in the 1960s developed the bootstrap model for the strong interaction and was strongly driven by considerations of uniqueness (Cushing, 1990). David Gross reflected on the influence of Chew, his PhD supervisor: "We were not merely doing phenomenology of the strong interactions, but were embarked on a great adventure to find a unique theory of hadrons. Geoff inspired us to think big, in particular to search for uniqueness in physical theories" (Gross, 1985a, pp. 128-129). For Gross, the potential of uniqueness formed a large part of his positive appraisal of string theory:

---

[5] For a historical introduction see (Kragh, 2009), for an introductory philosophical survey see (Tegmark, 2009).

> “One of the most exciting features of these string theories, which have the possibility of containing all known low energy physics, is their large degree of uniqueness. If a unified string theory turns out to be correct, it could not only allow us to calculate all of Eddington’s fundamental constants but could even determine the number of spatial dimensions.” (Gross, 1985b, p. 136).

The situation in 1985 was strikingly different to the current picture which is dominated by the landscape. In 1985, during the period known as the first superstring revolution, it was believed that there were only five distinct and consistent string theories (type I, type IIA, type IIB, and two flavours of heterotic string theory (SO(32) and $E_8 \times E_8$), and it is to these that Gross refers in the above positive assessment of the potential of string theory (Gross, 1985b).

In 2005, faced with the landscape scenario and potentially 10^{500} string theories, one panel at the Strings 05 conference was dedicated to the ‘next superstring revolution’. The panel featured eight of the most influential string theorists: Raphael Bousso (UC Berkeley), Shamit Kachru (SLAC[6] & Stanford), Maldacena (IAS[7], Princeton), Strominger (Harvard), Polchinski (KITP[8] & UC Santa Barbara), Ashoke Sen (Harish-Chandra Research Institute), Nathan Seiberg (IAS, Princeton), and Eva Silverstein (SLAC & Stanford), and was moderated by Steve Shenker who encouraged the audience to be “impolite”. Shenker described the initial pull of string theory’s claim to uniqueness: “there was the most amazing sense that quantum gravity was special and unique and it took delicate miraculous mechanics to unify quantum mechanics and gravity. It was really exhilarating. But that sense of uniqueness and distinctiveness has receded”. In response to this, the panel divided, with some arguing that uniqueness should be abandoned. For Gross, there was only one option as it concerns uniqueness, which he declared in his closing remarks at the Strings 03 conference quoting Churchill: “Never never never never never give up” (Gross, 2003).

4.1.2 Arguments against the necessity of uniqueness

In contrast to the claims concerning the fertility of string theory on the basis of uniqueness, which proceeded without argument, historical arguments concerning past fertility were advanced against uniqueness[9]. In this case the expectation that string theory should be unique was so strong that deviation required explanation. However, in contrast to the historical examples discussed by Elgin, instead of introducing a problem that needed to be resolved, Susskind and others put forward arguments to support their claims that uniqueness ought to be abandoned. Much of Susskind’s popular book, *The Cosmic*

---

[6] SLAC National Accelerator Laboratory, originally named Stanford Linear Accelerator Center.

[7] Institute for Advance Study.

[8] Kavli Institute for Theoretical Physics.

[9] Elgin has also noted that these asymmetrical treatments are typical (Elgin, 2020).

Landscape, is devoted to a rejection of uniqueness (Susskind, 2005). Susskind characterised the situation thus:

> "During the 1990s the number of possibilities grew exponentially. String Theorists watched in horror as a stupendous Landscape opened up with so many valleys that almost anything can be found somewhere in it ... Judged by the ordinary criteria of uniqueness and elegance, String Theory has gone from being the beauty to the beast." (Susskind, 2005, p. 125)

Arguing that uniqueness was a myth that has existed since the time of Pythagoras and Euclid, Susskind has argued that uniqueness is more a question of taste rather than necessary criterion for a theory of physics (Susskind, 2005, pp. 111, 118). In a similar vein, theoretical particle physicist Schellekens has argued that, "historically, whenever alternatives were imaginable, the hypothesis of uniqueness has almost systematically been a failure" (Schellekens, 2008, p. 2). Citing examples such as the historic belief that the earth is unique in being located at the centre of the universe, Schellekens argued against what he called the 'classic anthropocentric' arguments for uniqueness and concluded that we should put no stock in the uniqueness of our universe. If our universe is not unique, there is no need for unique unification. Susskind and Schellekens make historical claims to counter the long held aspirations to uniqueness, which they hold to be a mistaken constraint.

4.2 Anthropic reasoning and the landscape solution

In Susskind's 2003 paper, he also proposed that environmental or anthropic reasoning could be used as a selection principle that would reduce the size of the landscape. Susskind argued that "in an anthropic theory simplicity and elegance are not considerations. The only criteria for choosing a vacuum is utility, i.e. does it have the necessary elements such as galaxy formation and complex chemistry that are needed for life" (Susskind, 2003, pp. 4-5). Following Susskind's 2003 paper, Smolin wrote a direct response challenging the legitimacy of Susskind's approach titled 'Scientific Alternatives to the Anthropic Principle' (Smolin, 2004)[10]. A second public debate concerning the anthropic principle occurred, but on a much larger scale at the conclusion to the aforementioned panel at the Strings 05 conference. During his short presentation, Polchinski argued that the third revolution had already occurred, stating: "Steve and several other people have said to me 'so Joe, what are you going to say about the anthropic principle' but I guess I took his instructions too literally to talk about the next superstring revolution because by my count this is the one that has just happened" ("The Next Superstring Revolution", 2005).

As the number of possible values of physical parameters provided by the string landscape increased, Weinberg argued that "the more string theory legitimates anthropic reasoning as a new basis for physical theories" (2009, p. 39). On this view, physicists will have to resign themselves to exploring the vast terrain of the string landscape. Weinberg admits that such theories "certainly represent a retreat from

---

[10] This trigged a series of emails between the two authors, culminating in each writing a single letter to the other that would be published at the same time on the website 'The Edge' (Smolin & Susskind, 2004).

what we had hoped for: the calculation of all fundamental parameters from first principles", but "we may just have to resign ourselves to a retreat" (Weinberg, 2009, p. 39). In a similar vein, Polchinski remarked that "anthropic reasoning runs so much against the historic goals of theoretical physics that I resisted it long after realizing its likely necessity" (Polchinski, quoted in Roebke, 2005).

The debate over anthropic reasoning is often described as a divide between two styles of physics: East Coast versus West Coast. The two styles are supposedly characterised by institutional affiliation in the United States, where Stanford, on the West Coast, is considered a locus for research constrained by the anthropic principle and on the East Coast, Princeton, Harvard and others remain against such usage. This characterisation does not match the messiness of reality. For one, it is a very US-focused picture of quantum gravity research and does not consider the many high-profile individuals such as Martin Rees (from the UK), Sen (from India) and Smolin (from Canada) who have engaged in the debates. It also implies a simplistic divide of 'for' and 'against' when, as I shall argue in the following section, there were a variety of points of conflict concerning alternate positions on the aim of science.

4.2.1 Arguments for the explanatory power of anthropic reasoning

Pre-empting that his suggestion would be, at least initially, unpopular, Susskind outlined his argument for the potential of anthropic reasoning:

> "With nothing preferring one vacuum over another, the anthropic principle comes to the fore whether or not we like the idea. String theory provides a framework in which this can be studied in a rigorous way. Progress can certainly be made in exploring the landscape. The project is in its infancy but in time we should know just how rich it is." (Susskind, 2003, p. 17)

The idea behind the use of anthropic reasoning, as applied to string theory, was to turn the string theory landscape from problem to solution in order to answer a separate problem: the unexpected value of the cosmological constant. Without a formula to predict accurately the value of the cosmological constant (QFT is off by a factor of 10^{120}), it was instead proposed that, rather than being a constant of nature, the cosmological constant is an environmental constant. This argument claims to avoid having to answer to the questions of apparent fine tuning in the case where it appears that life is only possible for a very precise vacuum energy. This is because anthropic reasoning 'explains' the unexpected value of the cosmological constant because in a space of 10^{500} vacua it is to be expected that life would find itself in a universe with a vacuum energy such that life could exist and that the other universes would remain (mostly) unpopulated as the conditions are not conducive to life. Susskind utilises an understanding of explanation that is reminiscent of Hempel (1965), that is the behaviour is expected when a string world picture is applied. This became known as "the landscape solution to the cosmological constant problem" by some (Bousso, Freivogel, & Yang, 2009, p. 47).

4.2.2 Arguments against the necessity of anthropic reasoning

The critique of anthropic reasoning comes in two forms. The first is that any cosmological theory that is constructed with guidance from anthropic reasoning will be in principle non-predictive and therefore unscientific. Famously Ellis and Silk expressed concern, in an op-ed piece in *Nature*, at what they perceived to be a “change in how theoretical physics is done” away from empiricism (Ellis & Silk, 2014, p. 321). Citing the multiverse interpretation as a catalyst for their concern, they argued that “physicists, philosophers and other scientists should hammer out a formal narrative for the scientific method that can deal with the scope of modern physics” (Ellis & Silk, 2014, p. 323). The second critique is that anthropic reasoning is a methodological ‘cop-out’, or an *ad hoc* manoeuvre, and that any approach guided by anthropic reasoning is unlikely to produce interesting results and as such will restrict or even prevent future progress. That second critique, the focus here, is concerned with the explanatory aim of a theory of quantum gravity.

4.2.3 The ‘cop-out’ argument and the (non)-fertility of anthropic reasoning

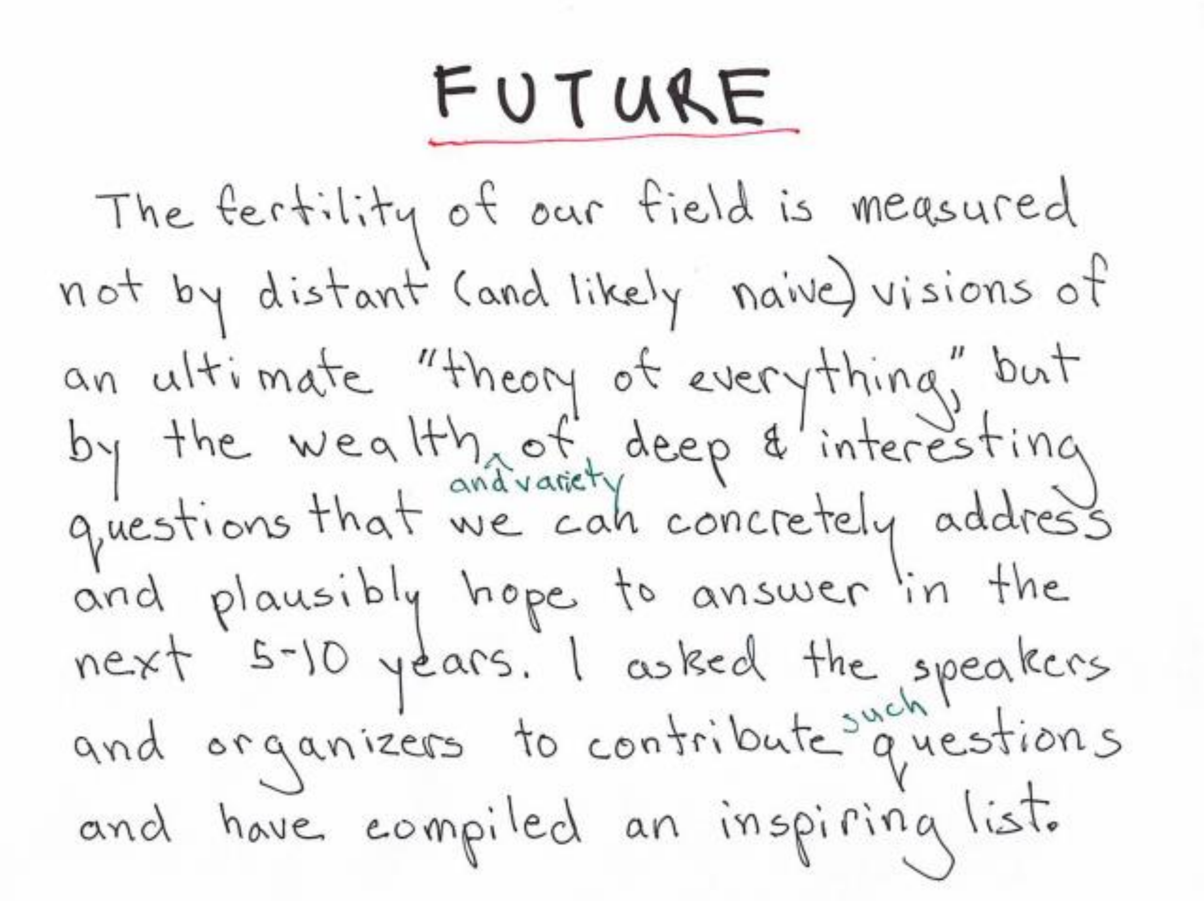
There are many who argued that the absence of a dynamic selection principle does not justify the use of the anthropic principle as a selection mechanism. Motl has argued that “the ‘anthropic principle’ is a philosophical paradigm designed to reduce our curiosity about the patterns in Nature” (Motl, 2004). Motl delivered his argument for use of anthropic reasoning as ‘defeatism’ that will deter future progress:

> “I think that it is a very wrong approach to science. One might have stopped the progress in science at virtually any moment in the past by claiming that some not-quite-understood features of reality are consequences of unexplainable dynamics involving zillions of Universes … and the only reason why reality behaves the way it does is that if it behaved otherwise, we would not be here.” (Motl, 2004)

Similarly, during his short presentation at the Strings 05 panel, Strominger urged the audience to avoid anthropic reasoning, arguing: “I have no logical objection to the anthropic principle. It could be true that there are some things we can explain anthropically. But it just doesn’t look like to me that we are going to learn anything interesting … nothing interesting is going to come out of it” (“The Next Superstring Revolution”, 2005). After the aforementioned debate that occurred at the end of the panel discussion, moderator Steve Shenker put to the audience the question whether: “by the year 3000, say, the value of the cosmological constant would be explained by the anthropic principle or by fundamental physics” (“The Next Superstring Revolution”, 2005). The panel spilt evenly but the majority of those in attendance voted against the anthropic principle; Aaron Bergman put the numbers at around 4:1 (Bergman, comment on Woit, 2005).

5. Constraints and Divergent Assessments of Fertility

> "The philosophy underlying loop gravity is that we are not near the end of physics, we better not dream of a final theory of everything, and we better solve one problem at the time, which is hard enough." (Rovelli, 2013, p. 16)



FUTURE

The fertility of our field is measured not by distant (and likely naive) visions of an ultimate "theory of everything," but by the wealth and variety of deep & interesting questions that we can concretely address and plausibly hope to answer in the next 5-10 years. I asked the speakers and organizers to contribute such questions and have compiled an inspiring list.

Figure 2 'Future' (Strominger, 2014)

This paper has introduced and analysed historical examples of non-empirical assessment in the context of the string theory debates. Dawid has claimed that such assessments are motivated by 'final theory' claims (Dawid, 2013a, 2013b), however such claims are rare in the string theory debates (Wienberg's *Dreams of a Final Theory* (1993) being a notable exception). Indeed, in the examples above and debates discussed in this paper a notion of a "theory of everything" was rejected by Strominger, Rovelli, and Johnson. At the 'Why Trust a Theory' conference, Gross also rejected the idea of a final theory, arguing that he was broadly agnostic to the concept, but said that he saw no signs that a final theory was close and was sceptical that a final theory could be found. For Gross "the issue in confronting the next step is not one of ideology but strategy: what is the most useful way of doing science?" (Gross, quoted in Wolchover, 2015).

Dawid has also argued that the divergent assessments of string theory are evidence for a meta-paradigmatic rift between a "classical" and a "novel" form of scientific theory appraisal (Dawid, 2009, p.986, 992). However, instead of an emergent paradigm that rejects a traditional, or empirical, understanding of scientific methodology, engagement with historical examples of appraisal highlights that there is a complex array of points of conflict, with each point of conflict centring on a different constraint. Rather than disagreement between two competing forms of appraisal, amongst those critical and those supportive of string theory, a high level of agreement was found as to the commitment to the relevant constraints, but disagreement as to the sufficiency of consistency, the path to background independence and a non-perturbative formulation, and how to interpret the significance of applications. In addition, the string theory community itself was shown to be deeply divided as to the necessity of uniqueness and the legitimacy of anthropic reasoning. This shows that there is limited historical evidence from the string theory debates for an alternate paradigm. Furthermore, the string theory community, united under Dawid's description of a meta-paradigm, has internally debated constraints. Finally, there are many in the string theory community who wish to stick to what is considered to be a 'traditional' constraint (uniqueness) and who reject the legitimacy of anthropic reasoning[11].

Of course, I have not here refuted Dawid's normative claims concerning the rationality of belief in string theory as a final theory, or the rationality of pursuing string theory. However, the account in this paper does raises a concern for Dawid's arguments. Very few critics of string theory argue that it is not rational to pursue string theory; they see value in other approaches but do not argue that all research into string theory should cease, and so Dawid's argument does very little to defend string theory from existing critiques. It also raises the question of the significance of final theory claims.

Instead of final theory claims, the examples of non-empirical theory assessment outlined here were regulated by considerations of constraints. These varied assessments informed divergent claims as to the past and future fertility of string theory: whether string theory has the capacity to guide future research, as evidenced by past satisfaction of constraints, and the potential for future satisfaction of constraints. These were assessments of the value of string theory in guiding future research in quantum gravity: assessments as to whether string theory has and will be valuable as a means rather than an end.

One advantage of drawing upon constraints as a philosophical framework to attempt to understand the debates over string theory is that it gives a more descriptively rich picture of how non-empirical assessment can be expanded to look at alternate theories of quantum gravity. This is a framework that can be expanded to help understand the graveyard of abandoned attempts of theories of quantum gravity, which died on the basis of non-empirical assessments of the dissatisfaction of constraints.

Secondly, we are now in a position to examine the function of constraints in the string theory debates. As Galison has also argued, constraints define the field of inquiry (1995). As was shown in section three of this paper, there are a number of undisputed constraints in the string theory debates. Whilst these

---

[11] The debates over uniqueness and anthropic reasoning also have many historical precedents; for more examples see (Kragh, 2011).

constraints do not uniquely determine an approach, as can be seen with rival approaches to string theory such as the canonical quantum gravity program, they do provide a structure or reference frame for appraisal within the field of inquiry (quantum gravity). It has been long established that decisive experimentation is unlikely in the foreseeable future for any theory of quantum gravity. It is therefore inevitable that historically non-empirical theory assessment has occurred. In the case of string theory, as with alternative approaches, there are many who have a significant degree of trust in string theory to contribute in the future to a theory of quantum gravity. The structure provided by the undisputed constraints, where the constraints are common reference points for all in the debates, facilitates rational debate and appraisal, of past and future fertility, within the field of inquiry.

This paper does not, however, suggest that the structure is permanent. Two exceptions to this continuity emerged with the rise of the multiverse hypothesis and contested constraints. The necessity of uniqueness and the legitimacy of anthropic reasoning are two interrelated debates that occur within the string theory community. Each of these points of conflict, unlike the others discussed, sees individuals debating the introduction of a constraint, anthropic reasoning, and the potential rejection of a constraint, uniqueness. These debates are, following an understanding of how constraints may constitute structure for a research area, potentially the ‘deepest’ debates, as the resolution of these debates might result in changes to the structure. In stark contrast to the conventional picture of the string theory controversy (as two incompatible sides: string theorists against their critics), these are debates that divide string theorists. This conclusion again reinforces that there are many varied points of conflict in the string wars.

Acknowledgements

I would like to thank audience members at the workshop on ‘historical perspectives on non-empirical physics’ the MPIWG in Berlin for helpful feedback and suggestions, and the organisers for the invitation to speak. I would also like to thank Dean Rickles for helpful comments on an earlier draft. Finally, I would like to thank the anonymous referees commented generously and insightfully on previous drafts of this paper and I am grateful for their help in improving the paper.

Bibliography

’t Hooft, G. (2001). Can there be Physics without Experiments? Challenges and Pitfalls. *International Journal of Modern Physics A, 16*(17), 2895-2908.

’t Hooft, G. (2013). On the Foundations of Superstring Theory. *Foundations of Physics, 43*, 46-53.

Barbero, J.F. (2011) Black hole entropy: lessons from loop quantum gravity *Journal of Physic: Conference Series*. 314 (012003)

Bekenstein, J. D. (1973). Black Holes and Entropy. *Physical Review D, 7*(8), 2333-2346.

Bergman, A. (2006a). Not Even Wrong. Retrieved from https://golem.ph.utexas.edu/string/archives/000898.html

Bergman, A. (2006b). Not Even Wrong: The Failure of String Theory and the Continuing Challenge to Unify the Laws of Physics. Retrieved from http://zippy.ph.utexas.edu/~abergman/Review.pdf

Bousso, R., & Polchinski, J. (2000). Quantization of four-form fluxes and dynamical neutralization of the cosmological constant. *Journal of High Energy Physics, 2000*(06), 006.

Bousso, R., Freivogel, B., & Yang, I. S. (2009). Properties of the scale factor measure. *Physical Review D, 79*(6), 063513.

Camilleri, K., & Ritson, S. (2015). The Role of Heuristic Appraisal in Conflicting Assessments of String Theory. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics, 51*, 44-56.

Curiel, E. (2001). Against the Excesses of Quantum Gravity: A Plea for Modesty. *Philosophy of Science, 68*(3), S424-S441. doi: 10.2307/3080963

Cushing, J. T. (1990). *Theory Construction and Selection in Modern Physics: The S Matrix* Cambridge: Cambridge Univeristy Press.

Dawid, R. (2009). On the Conflicting Assessments of the Current Status of String Theory. *Philosophy of Science, 76*(5), 984-996.

Dawid, R. (2013a). *String Theory and the Scientific Method*. Cambridge: Cambridge University Press.

Dawid, R. (2013b). Theory Assessment and Final Theory Claim in String Theory. *Foundations of Physics, 43*(1), 81-100. doi: 10.1007/s10701-011-9592-x

Duff, M. (2013). String and M-theory: Answering the critics. *Foundations of Physics, 43*(1), 182-200.

Elgin, C. (2020). Epistemic Gatekeepers: The Role of Aesthetic Factors in Science in French, S., & Ivanova, M. (Eds). The Aesthetics of Science: Beauty, imagination and understanding. New York: Routledge. 21-35

Galison, P. (1995). Context and Constraints. In J. Z. Buchwald (Ed.), *Scientific Practice: Theories and stories of doing physics* (pp. 13-41). Chicago: Univeristy of Chicago Press.

Giddings, S. B. (2013). Is string theory a theory of quantum gravity? *Foundations of Physics, 43*(1), 115-139.

Greene, B. (1999). *The Elegant Universe: Superstrings, hidden dimensions, and the quest for the ultimate theory*. London: Jonathan Cape.

Gross, D. (1985a). On the Uniqueness of Physical Theories. In C. DeTar, J. Finkelstein & C.-I. Tan (Eds.), *Passion for Physics: Essays in honor of Geoffrey Chew including an interview with Chew* (pp. 128-137). Singapore: World Scientific.

Gross, D. (1985b). *Opening Questions.* Paper presented at the Workshop on Unified String Theories, Santa Barbara, California

Gross, D. (2003). *Closing Remarks.* Paper presented at the Strings 2003 conference, Kyoto.

Hawking, S. W. (1974). Black hole explosions. *Nature, 248*, 30-31.

Hawking, S. W. (1975). Particle creation by black holes. *Communications in Mathematical Physics, 43*(3), 199-220. doi: 10.1007/BF02345020

Hempel, C. (1965). *Aspects of Scientific Explanation and Other Essays in the Philosophy of Science*. New York: Free Press.

Johnson, C. (2006). More Scenes From the Storm in a Teacup, VI. Retrieved from http://asymptotia.com/2006/11/10/more-scenes-from-the-storm-in-a-teacup-vi/

Johnson, C. (2015). On Testability Retrieved from http://asymptotia.com/2015/05/24/on-testability/

Kachru, S., Kallosh, R., Linde, A., & Trivedi, S. P. (2003). De Sitter Vacua in String Theory. *Physical Review D-Particles, Fields, Gravitation and Cosmology, 68*(4), 04600-04601 – 046005-046010.

Kragh, H. (2009). Contemporary History of Cosmology and the Controversy over the Multiverse. *Annals of Science, 66*(4), 529-551. doi: 10.1080/00033790903047725

Kragh, H. (2011). *Higher Speculations: Grand theories and failed revolutions in physics and cosmology*. Oxford: Oxford University Press.

Maldacena, J. (1997). The Large N Limit of Superconformal field theories and supergravity. *arXiv preprint hep-th/9711200*.

Motl, L. (2004). The Anthropic Lack of Principles. Retrieved from http://motls.blogspot.co.uk/2004/10/anthropic-lack-of-principles.html

Motl, L. (2010). Andy Strominger and a black hole talk. Retrieved from http://motls.blogspot.co.uk/2010/10/edward-witten-connecting-quantum.html

Polchinski, J. (2004). M Theory: Uncertainty and Unification. In G. Buschhorn & J. Wess (Eds.), *Fundamental Physics — Heisenberg and Beyond* (pp. 157-166): Springer Berlin Heidelberg.

Polchinski, J. (2006). Guest Blogger: Joe Polchinski on the String Debates. Retrieved from http://blogs.discovermagazine.com/cosmicvariance/2006/12/07/guest-blogger-joe-polchinski-on-the-string-debates/#.VPh5M_nkdcQ

Pooley, O. (2017). Background Independence, Diffeomorphism Invariance, and the Meaning of Coordinates. In Lehmkuhl (Ed.), *Einstein Studies Series*. Boston: Birkäuser.

Rickles, D. (2008a). Quantum Gravity a Primer for Philosophers. In D. Rickles (Ed.), *The Ashgate Companion to Contemporary Philosophy of Physics*. Aldershot: Ashgate.

Rickles, D. (2008b). Who's Afraid of Background Independence? In D. Dennis (Ed.), *Philosophy and Foundations of Physics* (Vol. Volume 4, pp. 133-152): Elsevier.

Rickles, D. (2011). Quantum Gravity Meets &HPS. In S. Mauskopf & T. Schmaltz (Eds.), *Integrating History and Philosophy of Science* (Vol. 263, pp. 163-199): Springer Netherlands.

Ritson, S. (2016). *The Many Dimensions of the String Theory Wars*. PhD. Thesis University of Sydney

Ritson, S., & Camilleri, K. (2015). Contested Boundaries: The String Theory Debates and Ideologies of Science. *Perspectives on Science*, 23(2), 192-227.

Ritson, S. (2019) Probing novelty at the LHC: Heuristic appraisal of disruptive experimentation. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, *69*, 1-11

Roebke, J. (December 12, 2005). Surveying the Landscape. *Seed*.

Rovelli, C. (2001). Quantum Spacetime: What do we know? . In C. Callender & N. Huggett (Eds.), *Physics Meets Philosophy at the Planck Scale: Contemporary theories in quantum gravity* (pp. 101-122). Cambridge: Cambridge University Press.

Rovelli, C. (2003). A Dialog on Quantum Gravity. *International Journal of Modern Physics D, 12*(09), 1509-1528. doi: doi:10.1142/S0218271803004304

Rovelli, C. (2013). A Critical Look at Strings. *Foundations of Physics, 43*(1), 8-20.

Schellekens, A. N. (2008). The emperor's last clothes? Overlooking the string theory landscape. *Reports on Progress in Physics, 71*(7), 072201.

Schwarz, J. (1998). Beyond gauge theories. *arXiv preprint hep-th/9807195*.

Smolin, L. (2004). Scientific alternatives to the anthropic principle. *arXiv preprint hep-th/0407213*.

Smolin, L. (2006). *The Trouble with Physics: The rise of string theory, the fall of a science and what comes next*. London: Penguin.

Smolin, L., & Susskind, L. (2004). Smolin Vs. Susskind: The Anthropic Principle. Retrieved 23.5.2015, 2015, from https://edge.org/conversation/smolin-vs-susskind-the-anthropic-principle

Strassler, M. (2013a). Did the LHC Just Rule Out String Theory?! Retrieved from http://profmattstrassler.com/2013/09/17/did-the-lhc-just-rule-out-string-theory/

Strassler, M. (2013b). Quantum Field Theory, String Theory, and Predictions. Retrieved from http://profmattstrassler.com/2013/09/23/quantum-field-theory-string-theory-and-predictions/

Strominger, A. (2010). Black Holes-The Harmonic Oscillators of the 21st Century. *Harvard Physics Monday Colloquium Series*.

http://media.physics.harvard.edu/video/index.php?id=COLLOQ_STROMINGER_091310.flv&width=640&height=360.

Strominger, A., & Vafa, C. (1996). Microscopic origin of the Bekenstein-Hawking entropy. *Physics Letters B, 379*(1–4), 99-104. doi: http://dx.doi.org/10.1016/0370-2693(96)00345-0

Susskind, L. (2003). The Anthropic Landscape of String Theory. *The Davis Meeting On Cosmic Inflation*. March 22-25, Davis, USA

Susskind, L. (2005). *Cosmic Landscape: String theory and the illusion of intelligent design*. New York: Little, Brown and Co.

Susskind, L. (2011). Topics in String Theory 1. *Topics in String Theory by the Stanford Continuing Studies Program*. iTunes U.

Susskind, L. (2013). String Theory. *Foundations of Physics, 43*(1), 174-181. doi: 10.1007/s10701-011-9620-x

Tegmark, M. (2009). The Multiverse Hierarchy. In B. Carr (Ed.), *Universe or Multiverse?* (pp. 99-126). Cambridge: Cambridge University Press.

The Next Superstring Revolution. (2005). Retrieved 27.8.2015, from https://www.fields.utoronto.ca/programs/scientific/04-05/string-theory/strings2005/panel.html

Tong, D. (2012). String theory. *arXiv preprint arXiv:0908.0333*.

Weinberg, S. (1980). Conceptual foundations of the unified theory of weak and electromagnetic interactions. *Reviews of Modern Physics, 52*(3), 515-523.

Weinberg, S. (1993). *Dreams of a Final Theory: The search for the fundamental laws of nature*. London: Vintage.

Weinberg, S. (2009). Living in the Multiverse. In B. Carr (Ed.), *Universe or Multiverse?* (pp. 29-42). Cambridge: Cambridge University Press.

Woit, P. (2005). Panel Discussion in Toronto. Retrieved from http://www.math.columbia.edu/~woit/wordpress/archives/000218.html

Woit, P. (2006). *Not Even Wrong: The failure of string theory and the continuing challenge to unify the laws of physics*. London: Jonathan Cape Ltd.

Woit, P. (2010). Grading String Theory. Retrieved from http://www.math.columbia.edu/~woit/wordpress/?p=3206

Witten, E. (2005). Unravelling String Theory. *Nature, 438*, 1085.