# Chapter 10
# A 'Second Superstring Revolution' and the Future of String Theory

*String theory is not a theory of strings.*
Robbert Dijkgraff

The close of the 1980s and the beginning of the 1990s didn't have the same degree of excitement as the mid-1980s. Though superstrings were pursued with vigour following the various anomaly cancellation results and the construction of the heterotic superstring, there were still many nagging doubts as to the basic structure of the theory—the existence of an apparent 'super-plurality' of theories compounded these. As Joseph Polchinski puts it: "[s]tring theory went through this tremendous wave of activity in the 1984 to 1987–1988 period. From 1988 to 1995, there was a perception that it had slowed down. Now in retrospect, huge amounts of stuff were done in those days: mirror symmetry, D-branes, Neveu-Schwarz branes, supergravity. Huge amounts of stuff being done, but nobody knew that it all fit together".[1] Many of these doubts were eventually eased, to a large extent, by a cluster of events in which the notions of D-branes and duality are centre stage.

This final chapter covers these recent developments, and brings the story near to the present day. Naturally, since the dust has yet to settle on literally tens of thousands of papers, I will have much less to say and simply sketch some key discoveries and events rather than attempting to describe their precise historical development. In particular: the recognition of the importance of D-branes in string theory, the existence of dualities, the eleven-dimensional low-energy limit giving $E_8 \otimes E_8$ superstrings, the role of black holes in string theory and the counting of microstates (giving the correct Bekenstein-Hawking entropy), and the interpretation of the 'string landscape' (with the controversial aspects that go along with it). Characterising these new developments is an exploration of non-perturbative $g_s \rightarrow \infty$ aspects of the theory in a bid to gain a better understanding of what string theory actually *is*. This had the effect of bringing to light various features that were simply not visible in perturbative,

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[1] The quotations in the following sections are taken from an interview of Prof. Joseph Polchinski conducted by the author on March 18th, 2009. The complete transcript is available online at: http://www.aip.org/history/ohilist/30538.html.

D. Rickles, *A Brief History of String Theory*, The Frontiers Collection,
DOI: 10.1007/978-3-642-45128-7_10, © Springer-Verlag Berlin Heidelberg 2014

weak coupling behaviour. This bundle of developments is often called the ‘second superstring revolution’.[2]

## 10.1 Dualities, D-Branes, and *M*-Theory

The introduction of D(irichlet) branes is often traced to Polchinski’s 1995 paper “Dirichlet Branes and Ramond-Ramond Charges”. However, there was a slow steady progression leading to the appreciation of the concept’s importance, during which they were essentially introduced many times over, since the late 1980s. They were in fact fully introduced, more or less as they are understood today (though without the additional background information that grounds their present importance), and also named, in a 1989 paper written by Polchinski, together with his students, Jin Dai and Robert Leigh: “New Connections Between String Theories”.[3] This paper is also one of the first to really promote the importance of dualities in string theory as a way of understanding what it really is and what objects it really contains. However, the paper was relatively obscure until after 1995.[4] Michael Green [28] also had the concept at around the same time. Once again, we find that conditions needed to have ‘ripened’ in the appropriate way, so that the value, in this case of the D-brane idea, was properly appreciated and its potential utility within a range of problems (especially involving dualities and black hole physics) better understood.

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[2] The terminology of ‘second superstring revolution’ has its origins in a talk delivered at the Sakharov Conference in Moscow (in May, 1996) by John Schwarz (see http://arxiv.org/abs/hep-th/9607067). In fact, I think the term ‘revolution’ is rather more appropriate here than in the 1984 case since there are *genuinely* radically new concepts that emerge from this work. After 1994–1995 the way string theory was understood was dramatically and permanently altered. This goes beyond a simple ‘high impact event’. But, still, I’m not sure that the second revolution qualifies as a revolution either, at least not in the sense of Kuhn’s elucidation of the concept. There was a structure being investigated and tools and concepts were invoked to better understand that same structure. It wasn’t a case of *overturning* some pre-established framework—indeed, most of the essential concepts were discovered by the mid-1980s onwards, but were simply not integrated.

[3] Here they demonstrate that a theory with both open and closed strings in a spacetime with compactified dimensions, is equivalent (dual) to a theory of open strings in which their endpoints have been fixed to single hyperplane: a D-brane. Polchinski also discussed some of these ideas in his talk at *Strings 1989* (held in March of that year). Again the key concepts and terminology of D-branes are clearly present. For example, he writes (invoking T-duality in which $\langle m, n, r\rangle \rightarrow \langle n, m, \frac{\alpha'}{r}\rangle$): “Open strings can’t wind, so there are no states to get light as $r \rightarrow 0$. From the point of view of the open strings, the compactified dimension does not reappear. Indeed, one finds that the vanishing of the normal derivative of $X$ [the compactified coordinate] implies the vanishing of the tangential derivative of $X'$: the string endpoints are fixed on a hyperplane. This hyperplane is actually a dynamical object, the Dirichlet-brane, with a calculable tension $T' = T/\pi g^2$, where $g$ is the open string coupling. Far away from the D-brane in the dual theory one finds only closed strings” [51, p. 436].

[4] There were just three citations in 1990, followed by 5 in 1991, 2 in 1992, 0 in 1993, and 3 in 1994. Then 12 citations in 1995, followed by 89 in 1996, once it was better adapted to the research landscape.

Before we get to D-branes' successful uptake, there is another important and related discovery, by Witten, also from 1995 [77]. This is the discovery that eleven-dimensional supergravity theory is a low energy limit of the ten-dimensional Type IIA superstring theory (or a strong coupling limit of Type IIA supergravity in ten dimensions). The new ideas came from a study of the non-perturbative behaviour of superstring theories, where the coupling constant is very large. A vital part of this project was the discovery (again, a somewhat protracted evolution, and not yet complete) of *S-duality* operating within string theories, relating strongly coupled and weakly coupled heterotic string theories (or sectors of the same theory) in four dimensions via the (non-perturbative, modular) $SL(2, \mathbb{C})$ mapping.

The notion of S-duality was introduced into the string theory literature by Anamaria Font, Dieter Lüst, Luis Ibáñez, and Fernando Quevedo in 1990 [22].[5] They left it as a conjecture that there was strong-weak coupling S-duality in the compactified heterotic string theory, generalising David Olive and Claus Montonen's own conjecturing of electric-magnetic duality [47]. David Olive, together with his PhD student Claus Montonen, had conjectured in 1977 that, when quantized, the magnetic monopole soliton solutions constructed by 't Hooft and Polyakov,[6] form a gauge triplet with the photon. This correponds to a Lagrangian similar to the original Georgi-Glashow one (as they say, the simplest Lagrangian containing $U(1)$ (Dirac) magnetic monopoles that arise as solitons), but with magnetic replacing electric charge. They referred to this new symmetry as "dual invariance," which simply means that the physical predictions will be unchanged regardless of whichever action one uses to extract those predictions.[7] The duality has curious implications:

> In the original Lagrangian, the heavy gauge particles carry the $U(1)$ electric charge, which is a Noether charge, while the monopole solitons carry magnetic charge which is a topological charge. In the equivalent "dual" field theory the fundamental monopole fields, we conjecture, play the rôle of the heavy gauge particles, with the magnetic charge being now the Noether charge (and so related to the new $SO(3)$ gauge coupling constant) [47, p. 117].

The dual invariance involves an S-duality mapping $e \rightarrow 1/e$ (where $e$ is the square root of the fine structure constant), also interchanging the 'elementary' excitations

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[5] See also Schwarz and Sen's 1993 paper [60] and Ashoke Sen's paper from 1994 [64]. Chris Hull and Paul Townsend [38] had labeled the Type II superstring version of S-duality "U-duality" (where it is seen to be combined with T-duality). Several other developments are contained in Font et al. [22]. For example, they show that S-duality follows from a duality between the elementary heterotic strings and the compactified (wrapped) NS 5-brane—the latter 'heterotic 5-brane' had already been conjectured by Michael Duff ([19], section 6.1) (and also Andrew Strominger, in a UCSB preprint). They also discussed the possibility that S-duality can be given a *geometrical* interpretation, involving the compactification of 11-dimensional supergravity—later confirmed in the work forming the beginnings of $M$-theory. Finally, they also discussed the possibility that the heterotic string can obtained from a 11-dimensional membrane, compactified to 10 dimensions—again, later confirmed by the work in $M$-theory, as we will see below).

[6] As modified by Manoj Prasad and Charles Sommerfield in 1975 [56], and Eugène Bogomol'nyi (building on Prasad and Sommerfield's work) in 1976 [6] (later called BPS states).

[7] The impact of this paper has been highly significant in recent years (with a sharp rise in 1995, in fact), as can be seen from Fig. 10.1.

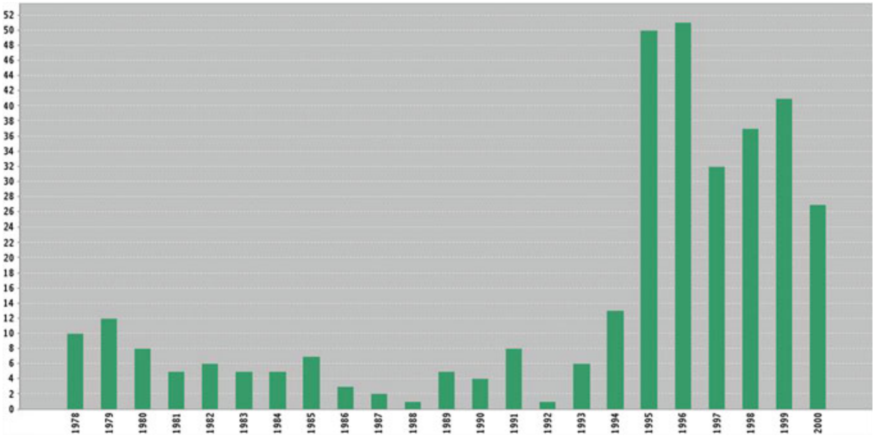

**Fig. 10.1** Graph showing the number of publications referring to David Olive and Claus Montonen’s paper “Magnetic Monopoles as Gauge Particles?” The spike in 1995, following the uptake of S-duality in superstring theory, is clearly visible. *Image source* Thompson-Reuters, *Web of Science*

(visible in perturbation theory) and the non-perturbative ‘solitonic’ (composite) excitations (that is, the electric and magnetic charges as in the above quotation). The Olive-Montonen *conjecture* was that there should exist a dual electromagnetic quantum field theory in which the roles of the elementary excitations and the composite solitons are exchanged. In order to *test* a ‘strong/weak’ S-duality conjecture like this, one clearly needs to probe throughout all values of the coupling, from weak to strong. Fortunately, the fact that the electrically charged particles and magnetically charged monopole solutions are (supersymmetric) BPS states, mentioned above, means that they benefit from the stability of such states under renormalization of the coupling constant.[8]

Strictly speaking, this work lies outside of string theory. Yet, part of Witten’s concern, in [77], was precisely to build a watertight case for the existence of S-duality in string theory—and also, crucially, to expand S-duality beyond the four-dimensional case. There was a sense, apparent from the opening lines of Witten’s paper,[9] that these ideas were pointing towards a deeper understanding of string theory. Ten years earlier, in his opening talk at the conference on Unified String Theories, in Santa Barbara, David Gross [29] had bemoaned the lack of a non-perturbative treatment of string theory: it was only known at weak coupling and, thanks to Gross’ own calcu-

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[8] Also, they exhibit a direct dependence between their masses (and tension) and the coupling strength, matching the central charge.

[9] Namely, “Understanding in what terms string theories should really be formulated is one of the basic needs and goals in the subject” [77, p. 85]. It is in this same paper that the terminology of a “web of connections between the five string theories and eleven-dimensional supergravity” (ibid., p. 87) first makes an appearance, though the concept had been suggested several times before, not least in [12].

lations, it was known that the perturbation series was not Borel summable. S-duality was precisely the tool that was needed to open up the non-perturbative regimes since it allows one to transform between theories at $g$ and at $1/g$, as with the electric-magnetic case above. In the string theoretic case, because all string theories contain gravity, the BPS solitons are a kind of black hole solution (of a supersymmetric theory) originally known as an "extreme" (now called *extremal*) Reissner-Nordström (charged) black hole. It turned out that D-branes provided a key component to make the concepts work in the string theoretic context.[10]

David Fairlie and Edward Corrigan had in fact discovered something very close to D-branes way back in 1975:

> One of the goals of the earlier period was to construct an off-shell theory, so that the string states could couple to currents. Edward Corrigan and I had a solution to this problem motivated by the analogue approach, by the introduction of Dirichlet boundary conditions; we used both the analogue and the operator methods to construct amplitudes with the correct properties. A general bosonic state can be expressed as $x^{\mu}(\sigma,\tau) = q + 2ip\tau + \sum a_n^{\mu} exp(in\tau) cos(n\sigma)$. ... One of the features of our paper was that the string would stop at a finite point of spacetime and latch on to a current, or a zero-brane in present day jargon. In our idea, the stopped strings would then interact with currents [21, p. 289].

What was missing from Fairlie and Corrigan's approach was, as Fairlie writes, the idea "to impose Dirichlet boundary conditions[11] in only a subset $d$ of the dimensions" [21, p. 290]. This paper was, of course, written as work on dual strings was entering its quietest period.

Michael Green [28] considered (toroidal) compactification of arbitrary numbers of target-space dimensions of a theory of orientable open strings. He begins by defining scattering amplitudes for interacting (oriented) closed and open strings using the sum-over-worldsheets idea, with worldsheet boundaries which have embedding

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[10] The extremality of the black holes in question refers to the fact that their masses are as small as is allowed for specified electric charges. They are in this sense already similar to D-branes: in this context they are D0-branes, like point particles. However, it is also possible for there to be 'black brane' (BPS) solutions, which have higher dimension. These would later prove crucial in stabilizing the size and shape moduli of the theory and in the string theoretic computation of black hole entropy (which suggested a resolution of the information paradox), which in turn prepared the ground for the Maldacena (AdS/CFT) conjecture.

[11] Dirichlet boundary conditions simply refer to a condition to cancel boundary terms associated with the ends of open strings, telling us how the end points behave: $X^{\mu}|_{\sigma=0,\pi} = 0$ (where we adopt the usual convention of parameterizing the string by having the spatial coordinate $\sigma$ take values in the interval $[0,\pi]$, and where $X^{\mu}(\sigma,\tau)$ are the fields describing the position of the string point $(\sigma,\tau)$ in the target spacetime). Depending on which values of $\mu$ one includes, one will have boundaries of different dimensionalities. Of course, for closed strings we find $X^{\mu}(0,\tau) = X^{\mu}(\pi,\tau)$, with end points identified. (Dirichlet conditions are contrasted with Neumann conditions, which demand that the normal derivative of $X^{\mu}(\sigma,\tau)$ vanishes: $\partial_{\sigma} X^{\mu}|_{\sigma=0,\pi} = 0$. Such a condition allows the end points to move freely, and in fact do so at the speed of light.) Clearly, however, the Dirichlet conditions *fix* the string end points to a particular location. The $X^{\mu} = 0$ constraint surface corresponds to a D-brane. As we will see below, Polchinski's breakthrough involved viewing these surfaces as physical, dynamical entities that correspond to expected nonperturbative effects in string theory (weighted by terms $e^{-O(1/g_s)}$).

coordinates into target spacetime that satisfy Neumann boundary conditions (roughly describing trajectories of open-string end-points). Compactifying onto a torus of scale $R$ he argues the theory is equivalent to a theory with "Dirichlet boundaries" (boundaries at fixed positions) on the T-dual torus, with scale $\alpha'/R$. He finds angular variables associated with boundaries (and conjugate to the boundary's winding numbers in the dual Neumann theory) which he interprets as the positions of the end-points of the strings. This duality is, he points out, an open-string version of T-duality: it implies that one can adopt the conventional Neumann picture of free open-string end-points or adopt the alternative picture of Dirichlet boundaries in the dual torus.

Polchinski [52] gave a modified formulation in which the boundaries (D-branes) carry Ramond-Ramond [RR][12] charges and are weighted by $e^{-O(1/g_s)}$ terms—as mentioned, the D-branes refer to 'defects' (with their own dynamics) characterised by the open strings attached to them. It turned out that these corresponded exactly to "particles" that Witten [77, p. 97] and others had predicted to exist in the Type II theory as a result of his investigations into the web of dualities (see below). They were, then, viewed as central to the enterprise of extracting information about the nonperturbative sectors of string theory, tightening up the web of dualities linking the various perturbative string theories, and figuring out what are the theory's fundamental degrees of freedom. This involved a kind of interlocking effect in which what had been viewed as separate skirmishes on apparently disconnected problems were seen to be joined together in a unified way.[13]

Polchinski describes his own, fairly long and winding journey to D-branes (and their acceptance as important pieces of the string theory puzzle) as follows[14]:

> The first piece was this paper ... with Yunhai Cai [50]. So there's the Green-Schwarz result that the anomalies in string theory cancel only in SO(32), and we wanted to understand in detail how that happened because we had already, which turned out in the end to be fallacious that we should be able to cancel them for any group. ... We in the end understood that the anomaly arose because a certain closed string field, a Ramond-Ramond field ... [a field in a

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[12] There are multiple 'sectors' of states in superstring theories, defined by the boundary conditions. For the closed superstring one has: NSNS, NSR, RNS, and RR (where 'NS' = 'Neveu-Schwarz' and 'R' = 'Ramond'). The NSNS and RR sectors describe bosons, while the NSR, RNS sectors describe fermions. As mentioned, it turns out that D-branes are sources of RR-charge.

[13] Polchinski expresses it as follows: "duality at the time had seemed to be a very sporadic and random thing [and Witten] explained how every single string theory had a strongly coupled dual, and how you would figure out what it is ... [s]o suddenly it became a framework and not just some oddity" (interview with the author).

[14] Note that Polchinski had written an earlier paper on "supermembranes" together with his students James Hughes and Jun Liu while at Texas (with Michael Duff's presence at College Station, supermembranes were something of a specialty there). This develops the idea of four-dimensional membranes in a six-dimensional supersymmetric gauge theory. There are no D-brane elements as such, but they close with an interesting speculation about our four-dimensional space-time being a membrane solution "lying in some higher-dimensional field theory" [37, p. 373]. The problem they raise with taking this seriously is that they are unable to obtain, from the underlying theory, the necessary spin-1, and spin-2 fields living on the membranes so that the gravitational force is not right in the membrane world. This has a strong whiff of Lisa Randall and Raman Sundrum's "alternative to compactification" model, where they focus on a 3-brane in five dimensions [57].

> certain sector of the string] . . . had an equation of motion that couldn't be satisfied. Now in the modern language, we had discovered that Dirichlet nine-branes carry Ramond-Ramond charge, so this is an important fact in the modern language, and it is fundamental to every talk you hear. But in those days, the idea of branes was not around; and secondly, *the importance of Ramond-Ramond charge was not around*, so we had resolved why would couldn't catch the anomaly, but anyway, it just sat there. (Interview with the author, emphasis mine.)

As David Gross notes, "[n]ew ideas in physics sometimes take years to percolate into the collective consciousness" [30, p. 9106]. This is certainly a case in point. Polchinski adds that they hadn't pushed the idea as much as they might have because "we also believed that the heterotic string was the theory of the world. This was just an exercise that we were doing" (ibid.). The second step involved duality symmetries in a more central way:

> The second predecessor work was this work with Dai and Leigh. The title is "New Connections Between String Theories", early 1989. I wanted to call it "Fun With Duality", but Rob Leigh was a serious guy and wouldn't let me do that.[15] So again, the T-duality was around, and by that time people were talking about it quite openly as evidence that strings had a minimum length size. . . . And the whole focus on heterotic string, everybody in the world was working on heterotic string because that was the one that seemed to be connected most closely to nature, and nobody ever asked what happens if you apply it to any of the other string theories: Type I, IIA, IIB. And it turned out these had interesting answers, because if you apply it to open string theories[16], then there's the story that the T-duality involves the winding modes of the closed string, but the open string doesn't have them, and in the end the only way you get a consistent picture is that the T-dual of the open string theory is a theory with a D-brane in it, and so in particular D9-branes are dual to D8-branes, D7-branes, D6-branes, and so on through a series of T-dualities. . . . In that paper we named D-branes and also orientifolds, which is another word you hear a lot these days. No one had ever asked what's the T-dual of an unoriented theory, and again it's non-trivial—instead of being a smooth space now it has an object in it, but it's sort of one of these orientifold planes. (ibid.)

These dualities were used to *reduce* the number of theories by establishing equivalences between them. They found that IIA, IIB, and Type I string theories were all dual—in terms of my earlier classification of pluralities, the Type 1 plurality had been reduced from 5 to 2 elements, and with it five families of ground states reduced to two families.[17]

A simple thought experiment led to the discovery of these dualities and with them the D-brane concept:

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[15] Polchinski did, however, manage to use this title in his *Strings '89* talk, for subsection II's heading [51, p. 435]!

[16] In fact, Kikkawa and Yamasaki [41, pp. 359–360] *did* briefly consider T-duality for open strings, but they found that the tension energy contribution was missing so that rather than achieving a minimum in a symmetric potential (i.e. for the effective potential), as discussed above (p. 178), $a_i = \sqrt{\alpha'}/R_i$ goes to zero. They note that the model consisting solely of open strings is, in any case, "unnatural" given the splitting and joining mechanism.

[17] Given this reduction Polchinski had wanted to write a follow up paper entitled "There is Only One String Theory" (interview with the author). Clearly this (and others like them around at the same time) were significant steps on the way to Witten's more systematic speculations about a single, unifying *M*-theory underlying all string theories.

> We know if we put a closed string in a small box we get T-duality in a big box. What if we just repeat this to the other string theories? And it partly began as a way to keep my students occupied, but it became a really interesting question when the answer wasn’t obvious. So we didn’t pre-suspect, but we discovered that these theories were all dual to each other. (ibid.)

The thought experiment in question involves a classic device in physics, namely putting a system in a box. Putting a quantum system in a box implies that you must have integer numbers of wavelengths in the box. Shrinking the dimensions of the box reduces the wavelength (and simultaneously increases the energy, in inverse proportion). Erwin Schrödinger had been aware of this implication at least as early as 1939 [58] and had used it to argue that the universe must be closed like a large box in order to provide an explanation for the atomicity of matter and light. Schrödinger also considered what happened as one varied the radius, as in the case of an expanding universe, but Polchinski et al. considered what happened as one shrank the box to a point. In this case a restricted set of states survive at the limit, as the box vanishes. This much is true for point-particles, but we are dealing with strings, and they interact quite differently with compact dimensions:

> For a closed string: now there’s the center of mass motion of the string. There’s a wave function for the center of mass of this string, which does the same things we just said. If there is any center of mass momentum, the energy gets very large, so we only have zero center of mass momentum. But a closed string can do something a particle can’t; it can wind, and it can wind many times before connecting back to itself. And as you make the box smaller, these states don’t have much energy because the string is not very long. What you find is that if you calculate the energies of the states in a very, very small box, the energy of the winding states in a very small box are exactly equal to the energy of the momentum states in a very large box. So this was the point of Sakai and Senda, and then again Frank Wilczek, Strominger, and the others explained it wasn’t just the spectrum but the interaction as well. You *cannot* shrink the box. It’s interesting, because it’s a thought experiment where you have the mathematics—you can do all the calculations, but then at the end of the day you have to look at it and say, “Hey, the physics is this.” And the physics is that you try to make the box smaller, but past a certain point what happens is a new spacetime emerges and the box gets bigger. That’s T duality. But if you do this with open strings, they can’t wind, and so what happens is when the box gets big, you have both open and closed. The box gets big, there’s a D-brane in there. And if you have unoriented strings, strings that can wind but they don’t have a direction—this actually is the part that puzzled us for the longest time—then you get a box with a wall an *O*-plane. So in some sense, these pictures were completely implicit in the original discussion. They were implicit in the technology of string theory, but no one had ever asked what is the actual physical picture that goes with the mathematics. (ibid.)

Though all of the central features of D-branes, along with their potential role in dualities, were in the published literature, the focus of the majority of string theorists at the time was to see how far one could get with Calabi-Yau compactifications of heterotic strings. We saw in the previous chapter that when attempts were made to generate realistic physics from non-heterotic strings problems quickly emerged. The question that caused a shift (itself a consequence of converging duality results pointing to a unique underlying theory) was: what are the objects that carry Ramond-Ramond charge that are demanded by S-duality? This created an explanatory gap that could be exactly filled by D-branes.

The explanatory gap, and the vision of a unified string theory that demanded it be filled, was presented by Witten at the *Strings 1995* conference, at the University of Southern California: http://physics.usc.edu/Strings95/.[18] The original talk was entitled “Some Comments On String Dynamics” and focused on determining the strong coupling behavior of various string theories in various dimensions. This was refashioned soon after into the paper “String Theories in Various Dimensions”. In this he had written:

> Apart from anything else that follows, the existence of particles with masses of order $1/\lambda$, as opposed to the more usual $1/\lambda^2$ for solitons, is important in itself. It almost certainly means that the string perturbation expansion—which is an expansion in powers of $\lambda^2$—will have non-perturbative corrections of order $\exp(-1/\lambda)$, in contrast to the more usual $\exp(-1/\lambda^2)$. ... The fact that the masses of RR charges diverge as $\lambda \to 0$—though only as $1/\lambda$—is important for self-consistency. It means that these states disappear from the spectrum as $\lambda \to 0$, which is why one does not see them as elementary string states [77, p. 91].

Witten’s paper itself caused a flurry of activity, as can be discerned from Fig. 10.2. At the conference, both Green and Polchinski knew about the objects Witten was describing: “Mike Green and I . . . looked at each other and said, ‘He must be talking about D-branes’ ” (interview with the author). Neither Green nor Polchinski were moved to immediate action, however. For Polchinski, the feast of ideas was a little too rich, and required some digestion, in the form of set of ‘homework problems’ to work through (with D-branes and open strings fairly low down on his list). The other reason was that the results were already out there, in his papers with Cai (showing that 9-branes carry Ramond-Ramond charge) and with Dai and Leigh (showing that 9-branes are T-dual to all of the other branes). This stance changed in August of 1995:

> I started working through Ed’s dualities for open strings, and actually I thought I found a contradiction. I thought I found that one of them was impossible, so I emailed Ed and we worked on it together. That was actually the first time I ever collaborated with him. But in the course of that collaboration, and also working through my homework problems, it suddenly was obvious. It’s one of these like the renormalization where all of the pieces were there, and suddenly you *know* that they’re all there. So I emailed Ed and said, “Oh, by the way, these D-branes carry a Ramond-Ramond charge, and they have these other properties”. I thought

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[18] At the same conference Michael Green’s talk on “Boundary Effects in String Theory” was devoted to D-branes, D-instantons, and stringy non-perturbative effects. Referring to Polchinski’s work, he states quite explicitly that “There are ... soliton-like ‘D-brane’ configurations whose rôle in the context of superstrings has not yet been illuminated . . . [that] might provide solitonic states that are needed if the suggested non-perturbative equivalence of the type 1 and heterotic theories is correct” (see the conference talk: http://physics.usc.edu/Strings95/Proceedings/pdf/9510016.pdf, p. 10). Chris Hull’s talk was on “Duality, Enhanced Symmetry, and ‘Massless Black Holes’. He writes of the “unexpected equivalences between string theories that look very different in perturbation theory [resulting] from different perturbation expansions of the same theory” pointing to cases in which “the strong coupling limit of a given theory with respect to a particular coupling constant is described by the weak coupling expansion of a dual theory, which is sometimes another string theory and sometimes a field theory” (http://physics.usc.edu/Strings95/Proceedings/pdf/hull.pdf, p. 1). I take this to show, similarly to the events surrounding the anomaly cancellation results (though much more so), that the field as a whole was poised at a critical point making it particularly receptive to the kind of unifying framework Witten proposed.

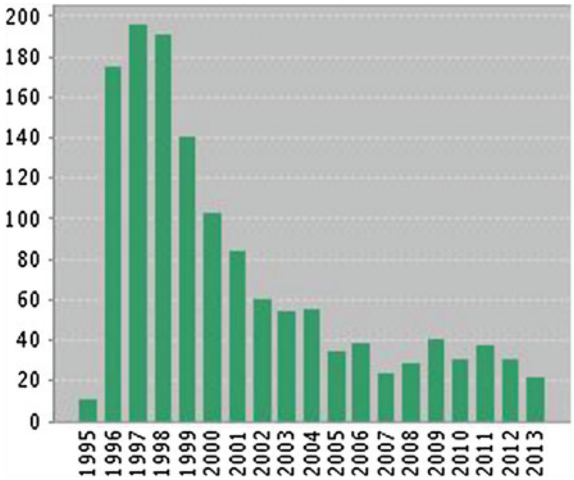

**Fig. 10.2** Graph showing the impact of Witten's paper "String Theories in Various Dimensions" in terms of the number of referring publications. *Image source* Thompson-Reuters, *Web of Science*

> it was neat. But I was not prepared for the response. He appreciated much more than I did how important this was. (Interview with author.)

Judging from Witten's original *Strings 1995* talk, and the other talks that were given there, I think it's fair to say that the full implications took some time to ferment in both Polchinski's and Witten's minds. Once it had, however, and their two papers were published, the impact was extremely dramatic:

> Within weeks of my paper, Vafa and Douglas and Sen had all pointed out important implications. I don't know of any episode like it in my experience where there had been such a change in a field. It's weird, because although I felt like I pulled the cork out of the dam, I didn't have any sense—it just blew me away. Why are they so important? Well, of course we suspected for a long time, and it was clear in my—I mean in my Les Houches lectures, I explained why string theory is not a theory of strings, and this was before any of this happened. It's clear that whatever the fundamental formulation of string theory is, D-branes are closer to it than strings. If you . . . ask today for what is our most complete formulation of string theory, either matrix theory, the Banks et al. one, or AdS/CFT duality, in both of those it's the degrees of freedom on branes that are the fundamental degrees of freedom. So it's pretty remarkable that there's all this stuff underlying string theory. (Interview with author.)

The impact of Polchinski's paper closely matches Witten's, and would have belonged to a pattern of co-citation (see Fig. 10.3).

The importance of the D-brane (re)discovery can be seen as involving an earlier argument of Steven Shenker [66], couched in Matrix theory, in which he shows that the $e^{1/g}$ versus $e^{1/g^2}$ behavior should be generic in string theory because string perturbation theory generically behaves like $(2g)!$ at genus $g$. Hence, since the perturbation theory diverges faster, this suggests that non-perturbative effects are likely to be much larger in string theories than in low-energy field theory. There were natural links to black hole physics stemming from this argument, as we will see in the next section, but first let us consider Witten's $M$-theory proposal in more detail.

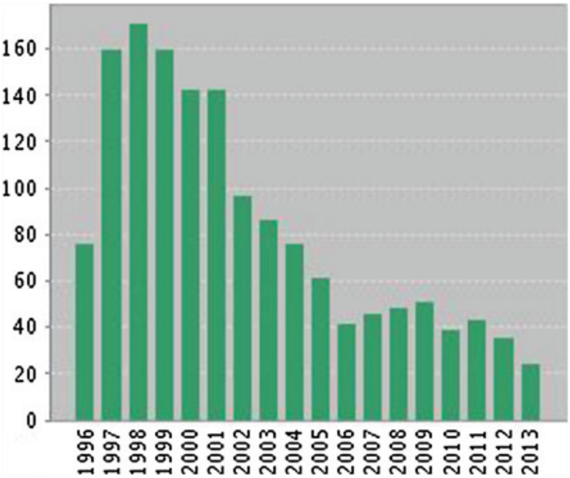

**Fig. 10.3** Number of publications referring to Polchinski's paper [53] following its publication in 1995. *Image source* Thompson-Reuters, *Web of Science*

As mentioned, Witten had introduced the notion of '$M$-theory' during a talk at a conference at the University of Southern California in 1995. $M$-theory is a conjectured theory postulated to explain the web of dual theories and provide further insights into the non-perturbative aspects of string theory. It would unify the disparate string theories, and bring order (and hopefully) uniqueness to string theory.[19]

One of the remarkable aspects of this web of dual theories (see Fig. 10.4), is that it involves theories of different dimensionalities, both ten- and eleven-dimensional. One can derive the various theories by compactifying $M$-theory on specific manifolds, and by exploiting the existence of dualities interconnecting them. For example, Paul Townsend demonstrated, early in 1995, that $M$-theory compactified onto the circle $S^1$ (or considering the behaviour of the eleven-dimensional theory on $\mathbb{R}^{10} \times S^1$), yields Type IIA superstrings. In his own words, since the $M$-theory concept had not yet been presented: "the type IIA ten-dimensional superstring theory is actually a

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[19] The first appearance of the term in print appears to be [62]. In a later popular article of Witten's we find the oft-quoted explanation of the letter '$M$': "M stands for magic, mystery, or matrix, according to taste" [80, p. 1129]. There's an ambiguity over the proper domain of $M$-theory, with e.g. Greene, Morrison, and Polchinski [27, p. 11039] assuming that $M$-theory simply refers to one of several limit points of a large parameter space that also includes the five superstring theories (i.e. the space of string vacua), while Witten appears to suggest that $M$-theory denotes the framework underlying *all* six of these limit points. On the former approach, both $M$-theory and the five superstring theories offer ways of describing whatever structure admits the large parameter space; on the latter approach the five superstring theories and eleven-dimensional supergravity offer ways of describing $M$-theory (the underlying, unknown structure) so that each limiting theory provides a physical scenario (fixed by values of the parameters) that is nomologically possible in $M$-theory, for certain settings. For example, the eleven-dimensional supergravity theory is seen to describe the long wavelength limit (see [78, p. 383]). The standard view that has emerged is that eleven-dimensional supergravity constitutes another low-energy limit of $M$-theory. Of course, whatever stance we adopt, it is clear that the underlying theory cannot be ten-dimensional, but must be an eleven-dimensional quantum theory (or perhaps something that completely transcends these old categories).

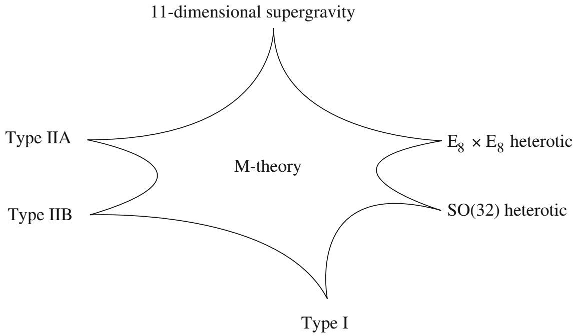

**Fig. 10.4** Edward Witten’s much copied diagram of the web of string theories linked by dualities, understood as limiting cases of a deeper theory. *Image source* [80, p. 1128]

compactified eleven-dimensional supermembrane theory” [76, p. 184]. Later that year, Petr Hořava and Edward Witten [33] extended this result, showing that compactification of an eleven-dimensional theory onto the orbifold $S^1/\mathbb{Z}_2$ (or considering the behaviour of the eleven-dimensional theory on $\mathbb{R}^{10} \times S^1/\mathbb{Z}_2$), yields heterotic $E_8 \otimes E_8$ superstrings.[20]

Hořava and Witten go on to consider further interconnections in $M$-theory’s web, due to the duality relations holding between the various theories. By using dualities between the heterotic $E_8 \otimes E_8$ and Type IIA theories (related to the eleven-dimensional theory as above), they are also able to include heterotic and Type I superstrings with $SO(32)$ gauge group in $M$-theory’s reach. The method involves a further compactification of $M$-theory, this time of the tenth dimension, onto a circle, so that one is considering the behaviour of $M$-theory on $\mathbb{R}^{10} \times S^1 \times S^1/\mathbb{Z}_2$. They explain the existence of the duality holding between these theories using the classical symmetries of $M$-theory thus compactified, with T-duality transformations taking one to the theories of $SO(32)$ strings.[21]

Type IIB theories were reached in a similar way by John Schwarz, using T-duality transformations [61], showing that IIB strings compactified on a circle correspond to the eleven-dimensional supergravity theory compactified on a torus. As Schwarz

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[20] The eleven-dimensional theory reduces to ten-dimensional strings since it contains 2-membranes which when compactified onto small circles appear as strings (see [18] for the earliest discussion of this idea, back in 1987). Of course, another way of putting this reverses the direction from reduction to emergence, so that at strong coupling (beyond perturbation theory) the ten-dimensional string theory ‘gains’ an additional dimension, with $S^1$’s radius increasing (as the two-thirds power) with the coupling strength—the ten-dimensional appearance of IIA strings is thus an artefact of perturbation theory. Note that this chapter [33] includes Witten’s own introduction of the $M$-theory concept into print, with the words: “The most ambitious interpretation of these facts is to suppose that there really is a yet-unknown eleven-dimensional quantum theory that underlies many aspects of string theory. . . As it has been proposed that the eleven-dimensional theory is a supermembrane theory but there are some reasons to doubt that interpretation, we will non-committally call it the $M$-theory, leaving to the future the relation of $M$ to membranes” [33, p. 507]. Hence, the $M$, and some of the central concepts surrounding $M$-theory, owe much to Townsend’s earlier efforts.

[21] Witten had already examined this heterotic–Type I string duality in [77], and then later with Joseph Polchinski [54], both in 1995.

notes, "[t]he remarkable thing about this kind of reasoning is that it works even though we don't understand how to formulate the M theory as a quantum theory" [62, p. 97]. Again, as we have seen previously, the curious behaviour of aspects of spacetime in string theory appears to point beyond a simple picture in which spacetime is fundamental. For example, at a lecture presented at the 29th International Ahrenshoop Symposium (in Buckow, Germany in 1995), Schwarz is led to state:

> The remarkable role of duality symmetries and their geometrically non-intuitive implications suggest to me that the theory might look very algebraic in structure without evident geometric properties so that no space-time manifold is evident in its formulation. In this case, the existence of space-time would have to emerge as a property of a class of solutions. Other solutions might not have any such interpretation [63, p. 3].

There remained a problem with the notion of $M$-theory: it was a rather abstract promissory note that required a precise construction or definition, which should result in a non-perturbative formulation of the theory. Several such attempts were made. We have seen how the eleven-dimensional theory was offered up as a potential source for a definition of the theory, in which the string theories are defined via various reductions.[22] A closely-related approach is the Matrix model[23] of Banks,

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[22] For example, Dijkgraaf, Verlinde, and Verlinde, write that "[b]y definition, M-theory is the eleven-dimensional theory that via compactification on a circle $S^1$ is equivalent to ten-dimensional type IIA string theory" [16, p. 43]. Of course, this really shows us the various limits of $M$-theory again, rather than pinning down the theory itself.

[23] It is interesting to note that in August of 1991, Paul Ginsparg established the first database ('hep-th' for 'high energy physics—theory'—a name Ginsparg attributes to Steven Shenker: [26, p. 4]) of what is now called "arXiv" (initially it was xxx.lanl.gov, but was renamed in 1998) to function as a repository for papers discussing the matrix model and "intended for usage by a small subcommunity of less than 200 physicists" (http://people.ccmr.cornell.edu/~ginsparg/blurb/pg96unesco.html.). There were just 160 initial users "assembled from pre-existing e-mail distribution lists in the subject of two-dimensional gravity and conformal field theory" [25, p. 159]—this mailing list might have been drawn from Joanne Cohn's list (she had attempted a 'manual' emailing approach to electronic distribution in 1991). The first chapter, http://xxx.lanl.gov/abs/hep-th/9108001, deposited on August 14th, was James Horne and Gary Horowitz's "Exact Black String Solutions in Three Dimensions". Another string theorist, Wolfgang Lerche, put Ginsparg onto Tim Berners-Lee's (then at CERN) new computer program: WorldWideWeb.app. (For more details on the history of arXiv, I refer the reader to Ginsparg's paper celebrating the 20th anniversary of the archive: [26].) As N. David Mermin would wryly remark, the archive might constitute string theorists' "greatest contribution to science" [46, p. 9]. In fact, string theory (and related areas) boast a surprising number of 'computer firsts': Green, Schwarz, and Witten's textbook was the first to be delivered camera-ready in $\TeX$—as he recalls, given the slowness of the computers in those days, "[e]very time I TeX'd a chapter, it would take about five minutes" (http://oralhistories.library.caltech.edu/116/1/Schwarz_OHO.pdf). Ginsparg also points out that he and Lance Dixon were the first to add their email addresses to a preprint. This suggests a curious possibility: is it possible that a scientific field might be pushed, to a fairly large extent, by the availability and early exploitation of easier and wider readership and easier (and wider) methods of communicating? Jokingly, John Schwarz claimed that string theorists' "main use of computers is likely to be to produce prettier preprints [but] more disturbingly is that we can also produce them faster" adding that "[i]f present trends continue we could reach a situation in which certain theorists turn out preprints as fast as the rest of us can read them" [59, p. 201]. If one is to think seriously about scientific revolutions in the period that coincides with the development of such tools as email, the internet, archive systems, and so

Fischler, Shenker, and Susskind[24] [3], which essentially reverses the direction, so that one considers how the eleven-dimensional theory *emerges* from a strongly-coupled limit of IIA theory. This leads to a definition of $M$-theory as the eleven-dimensional theory on a flat (“decompactified”), infinite background spacetime. The *matrices* in the name refer to the $N \times N$ matrices $X^i (i = 1, \cdots, 9)$ providing the coordinates of $N$ interacting $Dp$-branes in the target space.[25] The eleven-dimensional theory then emerges in the $N \to \infty$ limit.[26] This expedient allows one to probe the nonperturbative spectrum of a string theory.

The central problem with these was the same as with the definitions of string field theory: they were specified against some fixed background. What was (and still *is*) required, however, is a background independent formulation in which both the properties of the objects *and* the spacetime in which they propagate are determined by the theory. However, the idea of ‘emergent dimensions’ (with correspondences between radii of one theory and couplings of another theory) is a direct descendent of the same feature one finds in the so-called ‘Maldacena conjecture’ linking a gauge theory in four-dimensional Minkowski space with a string theory in $AdS_5 \times S^5$—it is, in turn a descendent of a *potpourri* of ideas, including ‘the holographic principle’ (a fact acknowledged in the Matrix model paper of Banks et al., [3, p. 5112]).

Schwarz had predicted (amongst many other predictions for the future of string theory) that “*It will be understood why six dimensions are compactified and three are not*” [59, p. 200]. While not exactly resolved by the developments in non-perturbative string theory, the meaning of the terms in the question itself have been transformed.

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(Footnote 23 continued)
on, one must consider the possible influences (and perhaps biases) they introduce. In fact, Roger Penrose [49] has argued that there might be a kind of path-dependence effect (along the lines of that found in the competition between VHS and Betamax video standards), whereby the spread of email and internet access, and with it the easy establishment of connections, allows for the spread of ideas so that a dominant trend can spread and become more entrenched because of such networks *even when the theories do not have standard experimental evidence supporting them* (cf. [75, p. 157]). Having said this, string theory might also have been amongst the last to use a ‘human computer’ to check results (and save then precious computing time): Michael Green pointed out (in a talk at a workshop in honour of John Schwarz) that CERN’s Wim Klein (a calculating prodigy that CERN had discovered doing calculations in Circus shows) would check difficult calculations for them and others—for more on Klein, see: http://home.web.cern.ch/cern-people/updates/2012/12/remembering-wim-klein.

[24] The Hamiltonian construction of their model depends on Susskind’s old tool of the ‘infinite momentum frame,’ that he had used in his earliest studies of the dual resonance model that had introduced the string and worldsheet concepts.

[25] Note, that these coordinates (being described by matrices) are non-commutative, which has been interpreted as implying a specific kind of ‘quantum geometry’ (see, e.g., [79]). However, as the authors of [3] admit, the microscopic degrees of freedom are not known, therefore it is hard to make this claim precise—interestingly, in 1988, Joseph Atick and Edward Witten had speculated about a “new version of Heisenberg’s principle [involving] some non-commutativity where it does not usually arise” noting that it “may be the key to the thinning of the degrees of freedom that is needed to describe string theory correctly” [2, p. 314].

[26] There are clear elements of this approach that hark back to ’t Hooft’s $1/N$ expansion from 1974.

Strominger, in his lecture[27] on “Black Holes and String Theory” argues that “the notion of space ... and time ... and dimension are not absolute.” He compares the situation to the phases of $H_2O$, and their temperature-dependence: in various regimes, water switches between solid, liquid, and steam. Just as we don’t have any problems making sense of this, so in the case of the dimension of spacetime, there is a dependence on the energy of the system: it becomes another dynamical parameter, in much the same way that the metric of spacetime is made dynamical in classical general relativity. This is, of course, one of the most radical implications of the more recent work on string theory, and is still being unpacked, though it clearly points towards problems with upholding ‘locality’ at a fundamental level.[28]

## 10.2 Black Holes, Information, and the AdS/CFT Duality

The study of strings in a more general class of non-compactified backgrounds began soon after the construction of the heterotic string.[29] Thinking about how string theory bears on the physics of black holes is, of course, a perfectly natural course of action given string theory’s claims to provide a theory of quantum gravity reproducing the classical equations of general relativity in the low energy limit. And indeed, in the low energy limit of string theories one can find solitons corresponding to black hole solutions. The D-brane technology allowed certain kinds of black holes to be constructed as configurations of coincident D-branes. However, the initial phase of string theoretic black hole research involved the study of strings on black hole *backgrounds*, rather than their construction and microscopic degrees of freedom.

In 1987, de Vega and Sánchez [14] studied the problem of a bosonic string in a $D$-dimensional Schwarzschild background, thus allowing for the study of strings on black hole spacetimes. Curtis Callan, Robert Myers, and Malcolm Perry suggested in 1988 that string theory might be useful for resolving some of the paradoxes that arise when considering black hole evaporation [8]. The idea is that the solutions of classical general relativity and string theory, though approximately identical at low energies (small curvatures), will differ at higher energies (strong curvatures). Given the improved ultraviolet behaviour of string theories, the hope was that it would forbid the formation of the singularities generic in Einstein’s equations. However,

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[27] Specifically, in answer to an audience question on whether string theory is eleven-dimensional: http://athome.harvard.edu/programs/sst/video/sst1_7.html.

[28] Interestingly, strikingly similar results—suggesting that locality is not fundamental, but must instead emerge from the physical degrees of freedom—can be found in a variety of approaches to quantum gravity, indicating that locality is very likely to be relativised in the physics of the future.

[29] In fact, so far as I can tell, Claud Lovelace [44] appears to have been the first to consider the behaviour of strings on curved space *before* the construction of heterotic strings, and even before the consistency proofs of Green and Schwarz. Lovelace was interested in the case of compactification on a hypersphere, rather than a hypertorus, as a way of generating a non-Abelian gauge theory. He argued, however, that compact Ricci-flat manifolds are restricted to Abelian symmetries, which restricts the compactification to those on a hypertorus once again.

Callan, Myers, and Perry focused on the reduced temperatures of black holes in the context of string theory (in comparison with solutions of Einstein's equations for black holes of the same mass), which they show to hold for multiple cases including heterotic strings in four-dimensions.[30]

Stephen Hawking and Jacob Bekenstein had demonstrated in the mid-1970s that black holes behave like thermodynamic objects, with a temperatures (emitting 'Hawking radiation' at $T_H = \hbar c^3/8\pi kGM$, with $M$ the mass of the black hole) and entropies (of $S_B = A/4G_N$, where $A$ is the area of the black hole's horizon).[31] The black hole will radiate its energy away, losing mass, eventually evaporating, leaving some kind of Planck scale remnant, or nothing at all. There is a paradox surrounding the quantum mechanical description of what happens to information that goes in to black holes given this Hawking evaporation. It appears that one could throw *pure* quantum states into a black hole and get mixed (thermal) states out, apparently in violation of unitarity, and resulting in a loss of information—this is often labeled the 'black hole information paradox.' Hawking believed that his analysis demonstrated that quantum mechanics is *violated* by evaporating black holes implying that the time-evolution of such a process had to be grounded in something else. In the context of quantum mechanics, entropy has a very specific combinatorial characterisation given in terms of the number of different quantum states a system might occupy. It seems natural to think, therefore, that if black holes are to be assigned an entropy then there ought to be an associated set of microstates. It became a challenge for any approach to quantum gravity to try and derive these microstates, and have them match the famous figure of Bekenstein. A second challenge was to see if Hawking's radical conclusion was correct. This set of ideas became a kind of thought laboratory for testing string theory, and other approaches to quantum gravity—it would also serve as a kind of testing zone for the newly incorporated D-branes.

One of the major breakthroughs, made possible by the discovery of D-branes, was the first calculation of the Bekenstein entropy for black holes, by counting their quantum states.[32] Though there were earlier attempts to compute black hole

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[30] Their analysis is based on Huang and Weinberg's demonstration that the Veneziano model possesses a highest possible temperature, namely the Hagedorn temperature (i.e. that beyond which there is an exponential rise in the density of particle states: adding heat creates particles that increase entropy, rather than increasing temperature) [36]. This chapter of Huang and Weinberg's is an interesting early application (just 2 years after the Veneziano formula had been written down) of the dual model to cosmological and gravitational contexts: I believe it constitutes the first such paper. What Callan, Myers, and Perry showed was that black holes also have a maximum temperature around the Hagedorn temperature.

[31] Bekenstein's reasoning was highly intuitive: given the irreversible growth of a black hole's surface area, and given entropy's similar irreversibly growing nature, the possibility is open to write the black hole entropy as a (monotonically increasing) function of this area. Bekenstein credits John Wheeler with suggesting the choice of ascribing a unit of entropy $k$ to something of the order of the square of the Planck length (see [5, p. 44]). This is, of course, related to the holographic principle which describes the non-extensivity of physics within some boundary (or 'in the bulk'): the degrees of freedom on the boundary suffice to determine the bulk physics, which contains surplus, unphysical degrees of freedom.

[32] We should also mention here that D-branes (though they called them *p-branes* in this case) were used in the context of black hole physics *before* their dramatic rise to fame in 1995. In a 1991

entropy [72], Strominger and Vafa [71] were the first to make the link, in 1996, for a highly idealised situation involving five-dimensional extremal black holes.[33] The microstates are then enumerated by counting the degeneracy of the BPS soliton bound states. The combinatorial aspects come about through Polchinski's identification of D-branes as sources of BPS states carrying Ramond-Ramond charge.[34] Hence, the problem reduces to counting bound states of D-branes. As an example, one can take the five-dimensional (extremal) Reissner-Nordström black hole. This is a solution of the equations of the classical supergravity limit of IIB string theory, with five directions compactified onto a five-torus $T^5$, with the black hole's 'charges,' $M, N, P$ determined by the ten-dimensional theory. In terms of D-branes, however, one directly compactifies the IIB theory onto $T^5$ around which $M$ D5-branes are wrapped, along with $N$ D1-branes (i.e. strings) wound around the circle, $S^1 \subset T^5$, which determine a quantized momentum $P$ (*á la* Kaluza-Klein compactification). One can *count* the states of the D-brane construction of the black hole solution by quantizing the open strings (with the momentum $P$) linking D1-branes to the D5-branes, which gives the simple expression: $S_D = 2\pi\sqrt{NMP} = S_B$.

Strominger and Vafa pointed out the potential relevance of their work to the black hole information paradox [71, p. 103]. They suggest that D-brane technology might be used to directly compute the low-energy scattering of quanta by an (extremal) black hole, to check for unitarity or its violation.[35] They note that S-type dualities could be utilised to make this a possibility, turning a strongly coupled problem to a weakly coupled one. Studying the Hawking radiation in terms of open string excitations, one finds that unitarity is indeed preserved.[36] This simple suggestion highlights just how interconnected the physics of strings (D-branes), black holes, and dualities was, and still is.

Many people followed Strominger and Vafa's approach, including Curtis Callan and Juan Maldacena [9] who derived the entropy, radiation rate, and Hawking temper-

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(Footnote 32 continued)
investigation of black hole solutions in ten-dimensional string theory, Horowitz and Strominger [34] show that there are extended black hole solutions (extended objects surrounded by an event horizon) that correspond to magnetically charged string soliton solutions (including 5-brane solutions). There was at this time, in fact, a fairly thriving industry studying black hole solutions via branes.

[33] Note, however, that the extremal black holes involve a zero-temperature approximation, and so are not thermal objects: of course, no Hawking radiation is possible in this zero-temperature limit. One can consider 'near-extremal' cases by perturbing around the extremal solution. In such cases, one can generate a small amount of Hawking radiation.

[34] I already referred to a kind of correspondence between D-branes and black holes: they share charge, mass, and tension. The D-brane based computation of black hole entropy confirmed this link.

[35] In D-brane terms, one can visualise black hole evaporation by picturing a surface (the D-brane) onto which a separate pair of open strings is stuck, which collide and join to form a closed string, which is then emitted off the surface as gravitational radiation as it becomes 'unstuck'.

[36] Amusingly, Schwarz 'predicted' in 1986 that there would be no loss of coherence in the string theoretic context, despite not having the tools available to do the analysis [59, p. 199].

ature from a similar analysis, generalised to non-extremal five-dimensional Reissner-Nordström black holes.[37]

These notions, and the idea of utilising a large-$N$ limit of coincident D-branes with dual descriptions, led to what might (given past naming conventions) be labeled a *third* superstring revolution: the gauge/gravity duality encapsulated in the AdS/CFT correspondence (where ‘AdS’ = ‘anti-deSitter’)—though, strictly speaking, it is more of an aftereffect of the cluster involving dualities, black holes, D-branes, and $M$-theory. The AdS-CFT correspondence (otherwise known as the Maldacena conjecture) is a radical duality based on the black-hole—D-brane (or open string/closed string) correspondence, and on an examination of their different limits. It involves the claim that a quantum theory with gravity is equivalent (in the sense of duality from previous chapters) to a quantum gauge theory without gravity: a string theory on anti-de Sitter space $AdS_5$[38] possesses equivalent physically observable properties to a conformal field theory defined on the (conformal) boundary $\partial\mathscr{S}_{\mathrm{AdS}_5}$. The degrees of freedom of one theory are transformed (by the duality) into the degrees of the other theory. As Polchinski puts it:

> This entropy counting is neat, but the gauge/gravity duality is amazing, because it really says that gravity and string theory are not anything new; they’ve always been present in the framework of quantum field theory or gauge theory, if we simply knew how to read the code, and Maldacena told us how to read the code. This has many implications. One is it does resolve the information problem at least implicitly, because it shows that you can formulate the quantum mechanics of the black hole in terms of the gauge theory which is purely quantum mechanical—it satisfies the ordinary laws of quantum mechanics. It shows that Hawking was wrong about the breakdown of the laws of quantum mechanics. What does break down in some sense is locality. The fundamental degrees of freedom in the gauge theory are not local in space time.[39]

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[37] Strominger, together with Maldacena and Witten [69], extended the analysis to the case involving compactification of $M \times S^1$ (where $M$ is Calabi-Yau 3-fold). The microscopic degrees of freedom of black holes are then represented by fivebranes wrapping around $P \times S^1$ (with $P$ a four-cycle in M). This brought the analysis of black holes back into the fold of $M$-theory. A series of progressive refinements and generalizations were made to the study of quantum black holes, but to discuss them would introduce an explosion of new literature.

[38] This is actually part of a product space with $\mathscr{S}_5$, an Einstein manifold (i.e. a solution of the Einstein field equations) of positive cosmological constant: it needs to be $S^5$ to get the symmetries of the gauge theory out correctly. Anti-de Sitter space is essentially like hyperbolic space with an additional time coordinate. It has a boundary and so one has to say what the boundary conditions are in any theory defined on this space. Of course, the scheme is not realistic: anti-de Sitter space has a negative cosmological constant, and in our universe it is apparently positive. There has been work on more realistic theories involving a dS/CFT correspondence (e.g. [70]), but this is still very much work in progress.

[39] There is a sense in which this feature is the non-perturbative counterpart of the kinds of conceptual problems that emerged in the 1980s through the consideration of spacetime/string interactions. The earlier predictions about profound changes that might be in store for the understanding of spacetime in string theory seem to have been realised to a large extent by the non-locality implications of the AdS/CFT conjecture.

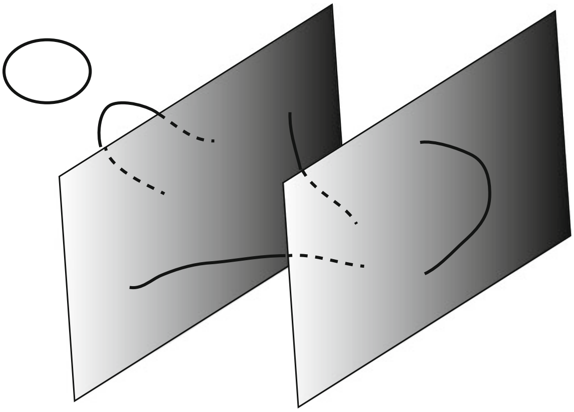

**Fig. 10.5** D-branes: with open strings on the same surface and stretched between distinct surfaces. Open strings correspond to gauge particles, closed strings to gravitons

This descriptive freedom in the languages (based around different degrees of freedom) one can use to describe the physical situation[40] of multiple D$p$-branes (gauge fields on flat worldvolumes versus gravitating objects embedded in string theory backgrounds) forms the core of the gauge-string duality in the AdS/CFT correspondence—one often speaks of a 'dictionary' for translating between languages. The AdS/CFT duality is, however, still restricted to a supersymmetric cousin of QCD.[41]

The duality, first presented in [45], involves the fact that at weak coupling D-branes don't warp spacetime geometry: they have a tension that is inversely proportional to the string coupling constant describing the strength of interactions. Therefore, at weak coupling (i.e. in the perturbative expansion for which $g_s \ll 1$) they will be unobservable.[42] At strong coupling D-branes *can* warp geometry, generating horizons just as black holes do: they have a tension that contributes to the stress-energy tensor which, if strong enough, will warp spacetime geometry near the D-brane. Strings can be bounded by pairs of D-branes (see Fig. 10.5) and when this happens the strings become massless (and are able to mimic gluons). The open string excitation spectrum contains a massless spin-1 particle, so that a D$p$-brane with open

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[40] Also clearly harking back to the earlier discussion of perturbative dualities (e.g. on 194).

[41] The conformal symmetry means, of course, that this supersymmetric theory is non-confining, since it is scale invariant: once one sets the coupling strength it remains at that strength independently of energy scale, unlike the QCD case. The supersymmetry is needed to stabilise the theory at high coupling. Hence, this cousin of QCD is a fairly distant one in that it does not possess asymptotic freedom and, as such, can provide only qualitative estimations of the non-perturbative behaviour of QCD proper.

[42] Though they will still have the description as a surface (in the full ten-dimensional spacetime) on which open strings are confined. Closed strings are free to move away from this surface (in the bulk). If open strings join to form a closed string then they too can move off the D-brane—physically, this corresponds to gravitational radiation being emitted from a photon.

strings attached has a $U(1)$ gauge field on its $(p+1)$-dimensional world-volume—hence, the open strings, in 1st excitation, will be described by a $(p+1)$D $U(1)$ gauge theory. When there are $N$ coincident D-branes (with open strings held between any pair of them) the gauge group is 'amplified' up to $U(N)$ (so that open strings are now described by a $U(N)$ gauge theory).[43] A stack of D-branes is essentially like a black hole again, warping geometry, thanks to the aggregated tension. In which case one ceases to talk about a 'D-brane stack,' and speaks of a 'mean gravitational field' (or a 'black brane'). But given the gravitational aspects, the object must now be part of a theory of *closed* strings.[44] D-branes can represent a gauge theory (open strings) at weak coupling, and a gravity theory (closed strings) at strong coupling.

The geometrical warping will be minimal, and the spacetime near flat, when $Ng_s \ll 1$. In this case, there can be both open and closed strings, but with low coupling strength they will be virtually decoupled from each other. The closed strings that decouple from the open strings give a picture of linearised, perturbative gravity. The open strings stuck to the D-brane, as we have seen (in the case of their low energy modes), are described by a gauge theory restricted to the D-brane (or D-brane stack). If we increase the coupling strength so that $Ng_s \gg 1$ then the gravitational effect of the D-branes on the spacetime metric becomes non-negligible, leading to a curved geometry and, in fact, a black hole geometry (or a black brane). By analogy with a standard Reissner-Nordström black hole, this geometry is $AdS_5 \times S^5$ (cf. [35, p. 174]):

$$ds^2 = \frac{r^2}{R^2}\eta_{\mu\nu}dx^{\mu}dx^{\nu} + \frac{R^2}{r^2}dr^2 + R^2 d\Omega_5^2 \tag{10.1}$$

Of course, strings sitting near the event horizon will be red shifted from the point of view of distant observers, and so will appear to have low energies. In the limit of low energies (ignoring massive states) the strings near the event horizon will decouple from the strings on the (flat) conformal boundary. Putting these two scenarios together, it follows that at weak coupling the physics is described by a gauge theory on flat space and at large coupling is described by a closed string theory on $AdS_5 \times S^5$. Maldacena conjectured that there was a duality linking these two descriptions together, by varying the 't Hooft parameter $\lambda_{'tHooft} \equiv g^2_{Yang-Mills} N_{colours}$, so that it was really one theory being viewed from different regions of parameter space.[45] The gauge theory—which is largely understood, e.g. in terms of observables and their

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[43] The gauge theoretic aspects arise from the fact that, as we have seen, the degrees of freedom on the brane are matrix valued, where the indices of the matrix $M_{ij}$ refer to the endpoints of the open string (if the endpoints lie on different branes then $i \neq j$).

[44] Polyakov refers to the slick manoeuvre of switching from a D-brane to a gravitational description as "a little like replacing the famous cat by its smile" [55, pp. 548–549].

[45] The holographic nature of the duality is evident from the fact that one is dealing with boundary data in the string theory. It is the boundary data that delivers the gauge field theory. The gauge theory lives on the $r \to \infty$ conformal boundary of $AdS_5$, with the string theory defined throughout the $r < \infty$ interior, i.e the bulk. This radial dimension (a 5th spatial dimension in the case of the string theory) is converted into an energy (or renormalization group) scale in the field theory on the

Hamiltonian evolution, and so on—includes in its (boundary) degrees of freedom all the information of the dual gravity theory (in the bulk).

Note that the apparent puzzle concerning the difference in dimensions of the two theories dissolves once one realises that they do not function as spacetime dimensions in both theories. The five dimensions of the string theory that appear to be missing in the gauge theory (from $S^5$) are retained as 'internal' degrees of freedom of the gauge particles: the full ten-dimensional spacetime coordinates of the string theory appear in the Yang-Mills theory as ten bosonic fields split between six scalar fields to describe D3-brane motion (one of these being the radial direction, and the other five being angles in transverse spatial directions that come from the matrix description of the branes) and four vector fields describing the low energy modes of the open strings stuck to the flat spacetime volume traced out by the D3 brane. The five angles map onto the 5-sphere component of the full product space while the Minkowski spacetime coordinates of the D3 brane (i.e. the worldvolume) and the radial direction map on to $AdS_5$. The symmetries are preserved between the theories by a mapping from the conformal symmetry of the Yang-Mills theory to isometries of the metric. Note that this also resolves a problem with the attempt to reconstruct the interior data from the boundary data (or vice versa) since *local* events on the boundary (i.e. observables that are close) can be far apart in the interior, but the energy-distance anti-correlation can (at least partially) account for this behaviour. This is how the four-dimensional gauge theory can encode the ten-dimensional gravity theory.

Given that one can describe black holes in string theory, using branes, one can ask about the system on the other side of the duality. Consulting the 'duality dictionary,' one finds a plasma of hot gluons: a thermal system. The Hawking radiation can likewise be translated into standard evaporation in the gluon system. This leads to an intuitive resolution of the Hawking information loss puzzle: the information is preserved, though it leaks out as in the evaporation of the gluon system. This is directly applicable to the black hole information puzzle: given the gauge theory/gravitational theory duality, if the former has no information loss (since the mechanism of such loss is absent in such a theory), then there cannot be information loss in the latter case.[46] Finally, and perhaps more importantly, the correspondence provides, in a similar way to the resolution of the information paradox, what might be the first non-perturbative definition of string theory. Gauge theories are well understood, and if there really is a strong-weak equivalence, then it can be used to tell us what the dual theory is. This is, more or less, where research on string theory stands today: trying to make better sense of the duality (and *prove* it in more certain terms) in order to better understand string theory.

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(Footnote 45 continued)
boundary such that events at distances far from the boundary correspond to IR processes and those near the boundary correspond to UV processes.

[46] There is a slight similarity to Gepner's resolution of the problem of the link between Calabi-Yau manifolds and solutions of the equations of string theory using conformal field theories (see p. 192). In that case, given the CFT-CY correspondence, if a CFT can be shown to be a solution then so must its corresponding Calabi-Yau manifold/s.

## 10.3 From Landscape Gardening to Anthrobatics

String theory gained a strong grip on the public’s imagination when, in 1988, a radio series on string theory, *Desperately Seeking Superstrings*, was broadcast, by the BBC. The show was conceived by Paul Davies who built it up around several interviews of famous physicists, some pro-string and some anti-string.[47] There continues to be a controversy about whether string theory deserves the preferential treatment it appears to receive: string theory is claimed to receive more funding and more fresh graduate students than it has earned the right to. As we have seen, the public controversy over superstring theory really began in 1985, with a spate of letters and notes bemoaning what was seen as a bad precedent for physics, jeopardising the historically-close bond between theory and experiment. A year later, Ginsparg and Glashow wrote:

> Contemplation of superstrings may evolve into an activity as remote from conventional particle physics as particle physics is from chemistry, to be conducted at schools of divinity by future equivalents of medieval theologians. For the first time since the Dark Ages, we can see how our noble search may end, with faith replacing science once again. Superstring sentiments eerily recall “arguments from design” for the existence of a supreme being [24, p. 7].

Of course, this was based on the fact that just as the heterotic string theory of Gross, Harvey, Martinec, and Rohm promised closer contact with the real world of low energy physics, the number of possible compactifications quickly dashed such hopes, spoiling predictive capabilities in the process.

The notion of a ‘landscape’ of string theories took some time to emerge, and came in several forms over a period of two decades.[48] We saw that, initially, in 1985, it was argued by K. S. Narain that there existed *infinitely* many (tachyon-free) heterotic string theories in $D < 10$. Narain associates the distinct string theories with the points of a coset manifold $M_d = SO(26-d,\ 10-d)/SO(26-d) \otimes SO(10-d)$. He also raises the question of which point, if any, nature selects, and why [48, p. 11]. These were not really viable models for our world. But they pointed very clearly to the fact that the consistency principles of string theory were not restrictive enough: there was still lots of freedom in the construction of consistent theories. Likewise, Andy Strominger, in 1986, wrote that:

> With the inclusion of non-zero torsion, the class of supersymmetric superstring compactifications has been enormously enlarged. It is barely conceivable that all zero-torsion solutions could be classified, and that the phenomenologically acceptable ones (at string tree level) might then be a very small number, possibly zero. It does not seem likely that non-zero torsion solutions, or even just the subset of phenomenologically acceptable ones, can be classified in the foreseeable future. As the constraints on non-zero torsion solutions are relatively weak, it does seem likely that a number of phenomenologically acceptable (at string tree level!) ones can be found... While this is quite reassuring, in some sense life has been made too easy. All predictive power seems to have been lost. All of this points to the overwhelming

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[47] This was released as a book in 1992: *Superstrings: A Theory of Everything?* [13].

[48] The ‘landscape’ terminology was introduced into fundamental physics by Leonard Susskind [73].

> need to find a dynamical principle for determining the ground state, which now appears more imperative than ever [68, p. 28].

Lerche, Lüst, and Schellekens are not so negative about such a large number of solutions: “Despite the presumably gigantic number of models that may exist, the possibilities are thus still severely limited in comparison with field theory in four dimensions” [42, p. 504]. That is, having a finite space of possibilities, however large, at least signals some promise of control and understanding.

In June 1986, Gell-Mann [23, p. 206] raised the spectre of anthropic reasoning (hanging over these expressions of horror at the vastness of the space of vacua), with respect to the question of “how Nature chooses among the physically inequivalent superstring theories, if we assume that one of them is right”. He considers three options, one of which is the idea that “Nature has arbitrarily chosen the one that agrees with our observations” noting that this “seems unpleasantly close to the strong anthropic principle”.

The failing uniqueness, once a central motivation of superstring theory (and a strong link to its bootstrapping past), appeared to be forcing a modification in the way the theory was to be understood. A similar shift was affecting cosmology according to Andre Linde (with a shift to an *inflationary model*, devised by Alan Guth), also writing in 1986:

> At present it seems absolutely improbable that all domains contained in our exponentially large universe are of the same type. On the contrary, all types of mini-universes in which inflation is possible should be produced during the expansion of the universe, and it is unreasonable to expect that our domain is the only possible one or the best one. From this point of view, an enormously large number of possible types of compactification which exist, e.g., in the theories of superstrings should be considered not as a difficulty but as a virtue of these theories, since it increases the probability of existence of mini-universes in which life of our type may appear. . . . The old question [of] why our universe is the only possible one now is replaced by the question in which theories [of] the existence of mini-universes of our type [are] possible. This question is still very difficult, but it is much easier than the previous one. From this point of view, an enormously large number of possible types of compactification which exist e.g. in the theories of superstrings should be considered not as a difficulty but as a virtue of these theories, since it increases the probability of existence of mini-universes in which life of our type may appear [43, p. 399].

Hence, Linde finds the existence of a plurality of worlds, predicted by a theory, a *good* thing, rather than a feature to be eliminated by finding appropriate selection or elimination mechanisms. However, the problem is that lack of uniqueness in pinning down the features of our world quite naturally results in a loss of predictive power (presumably one that scales with the departure from uniqueness). As Schwarz writes:

> Ideally, there would be just one consistent theory and it would have a unique stable vacuum. If that were the case then everything would be calculable from first principles. This is certainly the outcome that would be most satisfying. We have no guarantee that this is the way things are, however. At present, it seems at least as likely that there are large classes of stable vacua each characterised by a number of parameters. In this case one would imagine different choices are actually realized in different regions of the universe. Then the fact that a particular vacuum is selected in our little corner of the universe could not ever be understood as a logical necessity except perhaps using an anthropic principle. There would

> be no possibility of ever calculating some of the observed phenomenological parameters [59, p. 200].

These considerations form one kind of plurality. The existence of the various *types* of string theory points to another. However, the plurality that is behind the most recent string controversy includes the additional non-perturbative advances discussed in this chapter. In referring to the various vacua as “stable” Schwarz was unaware of (or was sidestepping) a hidden instability in their moduli. The problem is: what holds the compact spaces in place? What *constrains* them, preventing them from decompactifying to large dimensions, like our flat ones? When we take into account the method for correcting this (namely stabilization via flux compactification), the number of solutions becomes incredibly vast, with the standard estimate being around $10^{500}$—vast, but certainly more tightly constrained that Narain’s infinity of theories. Hence, as the conception of string theory has changed (with new tools and ideas being added, such as Calabi-Yau compactifications initially, and then D-branes), a persistent controversy concerning the theory’s predictive power has changed in tandem.

The problematic moduli in question are the Kähler and complex structure moduli parametrizing the size and shape of Calabi-Yau manifolds. These will be free to vary if left unconstrained.[49] Shamit Kachru, Renata Kallosh, Andrei Linde, and Sandip Trivedi (KKLT: [40]) speak of having to “freeze” such moduli, using flux to stabilize moduli in compactification schemes. In this case the flux is quantized so that the moduli values are also quantized in the process. The flux constrains the complex structure moduli, while D-branes have to be introduced to constrain the Kähler moduli.[50] This will determine a countable family of stable Calabi-Yaus. However, the number of possible manifolds, although forming a discrete family, is considerably larger than previous pluralities in string theory. A rough estimate that is often suggested, as above, is $10^{500}$ possible ground states.[51] This is the contemporary meaning of ‘string Landscape’ (corresponding to the previous chapter’s ‘ground state explosion’) but, as before (see p. xx), we find once again a split into two ways of viewing the plurality:

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[49] In the low-energy limit these moduli are like massless scalar fields, and so they can be changed without energy loss. In 1985, Michael Dine and Nathan Seiberg [15] had argued that the size modulus of a Calabi-Yau manifold would indeed decompactify to infinite radius, rendering unusable the whole compactification scheme (on which string phenomenology rested).

[50] In fact, the ‘turning on’ of fluxes in this way implies that the compact manifold is no longer of Kähler-type. Strominger [68] had already discussed such compactifications in 1986, when he studied compact spaces with torsion. This modifies the usual Cremmer-Scherk ‘Cartesian product space’ approach to the treatment of the compact and non-compact spaces, since the two lose their autonomy (and one speaks of a ‘warped product’ instead)—see Becker et al. [4] for an early discussion in the context of the moduli stabilization problem.

[51] A figure computed by assuming that shape moduli are restricted to some integer values, $n = 0, \ldots, 9$ (arising from the flux quantization), and combining this with the maximum possible Euler number for a Calabi-Yau manifold , assumed to be around 500 (based on current theoretical estimates and computer searches). The exact figure is not so important for the purposes of the debate. All that matters is that this number is, as Susskind so nicely puts it, “prodigiously large” [74, p. 285].

1. Treat the landscape's elements as corresponding to dynamical possibilities (once necessary identifications due to dualities have eliminated redundant points).
2. Find some mechanism or principle to break the plurality down to our world.

There are two controversial aspects with option 1: not only does it involve commitment to a gigantic ensemble of unobservable worlds; but in order to make sense of our own world within this ensemble, we must invoke the anthropic principle: we are **here**$_{existence}$ because we are **here**$_{location}$. That is, we find ourselves in this particular ground state (with its Yukawa couplings and particular particle content) because such a ground state (located amongst a plenitude of others) is necessary to support the existence of complex beings like ourselves. Were the values different (corresponding to a different **here**$_{location}$), we would not be **here**$_{existence}$.[52] As Susskind put it in his paper that introduced the terminology of *Landscape*: "The only criteri[on] 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. That together with a cosmology that guarantees a high probability that at least one large patch of space will form with that vacuum structure is all we need" [73, pp. 5–6].[53] That is, no *dynamical* selection mechanism is needed to sift through the possible worlds; nor is any ultimate consistency condition that eliminates all but one possible world.[54]

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[52] It is useful to compare this with Johannes Kepler's explanation for the planets' specific spacings from one another and from the Sun (as presented in his *Mysteruim Cosmographicum*). Kepler tried to deduce these distances from (geometrical) first principles, using a 'best fit' approach to the nesting of the five Platonic solids within one another, while considering the spheres in which the solids were themselves embedded as grounding the planet's relative distances. On this account, the explanation for the Earth's distance from the Sun, for example, is based on a mathematical scheme involving the regular polyhedra. Of course, the model was soon proved wrong by data, showing previously unknown planets that did not fit Kepler's scheme. The point is, however, that a more natural explanation in this context is simply that had the Earth *not* been at the distance it has (or thereabouts) there wouldn't exist beings such as ourselves capable of posing the question in the first place, since the conditions would not support complex life. Of course, this is over-simplified, and one might question various parts of the anthropic answer, but it clearly shows how an anthropic response might in some cases be a reasonable option. One might think a better response would look not to mathematical principles, but to physical principles: the evolution of galaxies and so on. This latter would perhaps be a closer match to option 2 above.

[53] As Susskind notes, the terminology of "Landscape" came from the study of systems with very many degrees of freedom, in which the metaphor of 'energy landscape' is employed [74, p. 274]. In this context one can find jagged graphs with peaks and valleys, such that the valleys are supposed to represent possible states of the system.

[54] This desire for 'one possible world' coming out of the equations ('one vs. many') might be seen as a throwback to Chew's *frustration* over arbitrariness in physics [10] (see also [11]). It is, perhaps, no accident that Chew's former student, David Gross, is one of the staunchest advocates of the 'uniqueness via selection' option. He was (and likely still is) of the opinion that such forms of reasoning should be "at best. . .the last resort of physical theory" [31, p. 105]. (I will just mention one example of what such a selection rule might look like (due to R. Holman and L. Mersini-Houghton: [32]). Their idea is that decoherence via the backreaction of matter degrees of freedom onto gravitational degrees of freedom can serve to reduce the number of allowed initial states of a universe. Generically, any cosmological model with both matter and gravity will exhibit non-ergodic behavior driven by out-of-equilibrium dynamics so that such universes must satisfy a superselection rule for the initial conditions—they also manage to pull out an explanation of the arrow of time from

Relative to this Type 3 plurality, Susskind adopts a stance more or less aligned with Linde.[55]

The standard argument against such a position is that it demolishes our ability to make predictions. This forms the basis of Lee Smolin's primary objections in his book *The Trouble with Physics*. Smolin strongly distinguishes examples such as the Keplerian one I gave above from the kinds of case involving the universe as a whole and the landscape. To change to Smolin's own example (see [67, p. 163]): why is the Earth so bio-friendly? The puzzle is easily resolved anthropically in this case because we have evidence of billions of other stars (and likely planets) and we will quite naturally find ourselves on a biofriendly one: how could it possibly be otherwise? This is the *weak* anthropic principle: it is generally accepted as valid, though rather trivial reasoning. If we apply the same question to the universe, instead of the Earth, then, the objection goes, we have no evidence of billions of similar universes, and so we cannot run the same argument. As far as the universe is concerned, we have a sample of one: our own.[56]

However, there have been attempts to derive predictions (or, more precisely *accommodations*) using the 'vacua + anthropics' package as a tool. Bousso and Polchinski followed this strategy in 2000 to calculate the value of the cosmological constant [7]. Their approach was simply to find a way to generate a large enough

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(Footnote 54 continued)
their scheme, based on the fact that the same non-ergodicity lowers the entropy of initial states, thereby allowing one to use the second law of thermodynamics *plus* this low-entropy past.

[55] Alan Guth credits Susskind with being one of the key spokespeople for (the original) inflationary cosmology's good 'public relations' (interview of Alan Guth, by Alan Lightman, September 21, 1987: http://www.aip.org/history/ohilist/34306_1.html). Susskind (together with Sidney Coleman) were in the audience of Guth's first talk in which he introduced the idea. However, when it came to the anthropic people, Guth was on the side of Gross: "I find it hard to believe that anybody would ever use the anthropic principle if he had a better explanation for something." Pointing instead to a future where we have better physics, he says: "I tend to feel that the [physical constants] are determined by physical laws that we can't understand [now], and once we understand those physical laws we can make predictions which are a lot more precise . . . my guess is that there really is only one consistent theory of nature, which has no free parameters at all". Of course, some would say that the anthropic Landscape *is* such a theory. (Note that Guth has since switched his allegiance: http://www.iop.org/about/awards/international/lecture09/page_38408.html—it seems clear that in his interview with Lightman, Guth was referring to a *strong* version of the anthropic principle according to which humans are somehow 'special' in the universe. If one has independent reasons to believe in a large enough ensemble of worlds to make worlds like ours likely within it, then one can adopt a weaker version of the principle along the lines of that given above, concerning the Earth's location.

[56] In fact, I think a case might be made for using Smolin's 'reasonable' usage of the anthropic principle (that one can explain away curious, apparent fine-tuning using an ensemble of similar cases) as providing some level of support for the universe-level case. The kind of fine-tuning one finds at the Universe-level is very similar to that at the planetary-level, and so one might reasonably assume that their solutions will be similar (especially so in the absence of any other reasonable alternatives). In other words, so long as one doesn't *restrict* one's evidence to just one finely-tuned universe, but also considers how a similar problem concerning the bio-friendly Earth is resolved (and perhaps other fine-tuning cases of a similar nature in which one has an observable comparison class available, as Smolin insists), then one could begin to mount a defence of the landscape.

space of string vacua to make those possessing a tiny (but non-vanishing) cosmological constant, like our own universe,[57] likely (and thus explain our presence in such a world). Susskind was following this same path. Michael Douglas also followed suit, again focusing on "physical questions this [ensemble] might help us resolve" [17, p. 1]. Douglas' approach was to attempt to better understand the details of the space of vacua by classifying its elements: "one must simply enumerate string/M theory vacua and test each one against all constraints inferred from experiment and observation" (ibid., p. 2). This approach has similarities to one suggested by Kawai, Lewellen, and Tye in 1987[58] which is clearly doing for the type-2 plurality what Douglas proposes for the type-3:

> It is also clear that in contrast to the 10-dimensional case the number of 4-dimensional chiral models is very large. As yet, a complete classification of all consistent string models is unavailable. In this work, we have given a complete treatment of fermionic string models in $D \leq 10$ dimensions obtainable from toroidal compactification in the fermionic formulation. This subclass of models is already quite large. In the first quantized formalism, all consistent string models should be treated on an equal footing. It is plausible that string dynamics may select a subset of the first quantized string models (i.e. second quantized vacuum states) as locally stable (e.g., by considering solutions of the (as yet unknown) closed string field theory). However, even if string dynamics eventually selects a unique ground state, it does not necessarily imply that this is the state representing our universe [39, p. 72].

So much by way of setting up the kind of early landscape scenario we have already seen. They continue:

> A systematic approach to test the string theory would be to completely classify all consistent four-dimensional chiral string models and then examine them one by one. We believe such a complete classification is a tractable problem and that the relevance of string theory to nature can be tested [39, p. 75].

Shortly afterwards, Antoniadis, Bachas, and Kounnas cautioned against such a 'brute force' approach, stating: "The number of consistent four-dimensional string theories is so huge that classifying them all would be both impractical and not very illuminating" [1, p. 104]. It is clear that the additional structure of the type-3 plurality makes the project more plausible. However, the task is ongoing.

It is often argued that string theory's contributions to mathematics are sufficient to warrant such inflated levels of support. Such mathematical contributions are impressive on their own merits, but they can often lead to unexpected physical results. John Ellis expressed this particularly clearly in the paper that introduced the title of 'theory of everything'[59]:

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[57] Of course, this tiny non-zero value is fixed by the acceleration of the universe's rate of expansion.

[58] Lerche, Lüst, and Schellekens had remarked earlier [42, p. 505] that one might be able to completely classify some subclass of the plurality of theories.

[59] As John Schwarz has pointed out, the phrase 'theory of everything' has tended to worsen the controversy: "The phrase "theory of everything," which has been used in connection with string theory, is a phrase I don't like myself and have tried to avoid. It was introduced by somebody else. There are several reasons I don't like it. One reason . . . is that it gives other physicists the impression that people who work in this field feel that their work is more important than what other people are

> Even if many features of [superstring theory] are wrong, new ideas are being brought into particle physics at a rate unequalled since the renaissance of gauge theory in 1971. Our intellects are being mathematically stimulated, and we are thinking of many new types of phenomena that our experimental colleagues can search for. We cannot discover the secrets of nature by pure reason, and must look to an experimental breakthrough. At the very least, the superstring may point us to a previously unmarked stone which, when turned over, may reveal interesting new life beneath [20, p. 597].

Ivan Todorov points out, in response to this kind of *argument from mathematical fertility* that the study of knot invariants was stimulated by the Haag-Kastler operator algebraic approach to local quantum theory[60] yet has not received anything like the kind of support as string theory has [75, p. 158]. Clearly, however, this is too simplistic. I have not seen it suggested that string theory’s mathematical achievements *alone* warrant such preferential treatment. Only that it is one component of a case built from very many achievements.

Murray Gell-Mann suggests that string theory might be following an entirely distinct path to that usually followed in the natural sciences:

> My attitude towards pure mathematics has undergone a great change. I no longer regard it as merely a game with rules made up by mathematicians and with rewards going to those who make up the rules with the richest apparent consequences. Despite the fact that many mathematicians spurn the connection with Nature (which led me in the past to say that mathematics bore the same sort of relation to science that masturbation does to sex[61]), they are in fact investigating a real science of their own, with an elusive definition, but one that somehow concerns the rules for all possible systems or structures that Nature might employ. Rich and self-consistent structures are not so easy to come by, and that is why superstring theory, although not discovered by the usual inductive procedure based principally on experimental evidence, may prove to be right anyway [23, p. 208].

There is a sense in which this debate over the fundamentals of the scientific enterprise harks back to a much earlier debate over the same issue, between Thomas Hobbes and Robert Boyle. Hobbes criticised Boyle’s experimental method for a variety of reasons, but especially pertinent is his assertion that experiments—Hobbes had in mind those involving the air-pump—are inherently defeasible, with any knowledge

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(Footnote 59 continued)
doing, and this creates a certain hostility or bad feelings. My personal feeling is that what we’re doing is interesting and important but what other people are doing is also interesting and important, and any phraseology that’s going to create a wrong impression I think is unfortunate. . . . Another is that I think it’s misleading, because even if we did solve all the problems we’re trying to solve, there would be many things that were not explained—it’s not a theory of everything. It’s a theory of something—something that’s very fundamental and very interesting. But there’s a lot more to the world than what you can learn from the basic underlying microscopic physical laws” (Interview with John H. Schwarz, by Sara Lippincott. Pasadena, California, July 21 and 26, 2000. Oral History Project, California Institute of Technology Archives. Retrieved [2nd Jan, 2012] from the World Wide Web: http://resolver.caltech.edu/CaltechOH:OH_Schwarz_J).

[60] Vaughan Jones’ work grew out of his studies of subfactors, which was related to the Haag-Kastler approach.

[61] Gell-Mann seems to have been at his most whimsical at this conference. In his lecture he also refers to the other speakers’ rapid-fire usage of the overhead projector as like a “tachistoscope,” accusing them of engaging in subliminal messaging!

generated from them likewise rendered defeasible (experiments can be rationally compelling though not deductively valid).[62] The experimental approach was victorious in the earlier debate. It remains to be seen whether string theory follows Boyle down the experimental path, or ends up closer to Hobbes. Certainly, in attempting to construct a theory with no free parameters, that explains all forces, all matter, and even their spatiotemporal framework, one is bound to face some difficulties in connecting with everyday experimental science!

## 10.4 The Future of String Theory

At a meeting on 'Unified String Theory' in 1985, David Gross laid out eight questions and problem areas that needed to be addressed [29]. He revisited these in a 2005 talk [31]:

1. How Many String Theories are There?
2. String Technology.
3. What is the Nature of String Perturbation Theory?
4. String Phenomenology.
5. What is the Nature of High Energy Physics?
6. What Picks the Correct Vacuum?
7. Is there a Measurable, Qualitatively Distinctive, Prediction of String Theory?

He saved an additional question for last: "8. What is String Theory?" Some of these questions become interlinked by 2005, especially the first and last. In addition to the older dualities, giving the "web of theories" (T-duality and the weak-strong coupling dualities), he mentions the AdS/CFT correspondence: this links backgrounds too, but also provides clues as to the question of what string theory is, since it provides a non-perturbative definition of the string theories involved in the duality—for this reason, question 3 is also clearly impacted on.

As we have seen, a persistent stumbling block since it was encountered in the mid-1980s has been the problems posed by the proliferation of string vacua, which has a direct bearing on questions 6 and 7 (and 1), probably the most important from the point of view of string theory's critics. The only known way pointing to some kind of solution it is to invoke the anthropic principle.

The key issue for string theorists is more probably: what *is* string theory? This might seem like a rather ridiculous question to pose after a book devoted to its not inconsiderable history, but there has yet to be presented a *principle* for string theory, and it remains to a large extent a framework of rules of thumb and techniques, albeit an incredibly fruitful and promising one. In the context of his 1985 talk, Gross was concerned that its methods of construction, "often producing, for apparently mysterious reasons, structures that appear miraculous" [31, p. 104] was problematic:

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[62] See Steven Shapin and Simon Schaffer's book *Leviathan and the Air-Pump* [65] for the locus classics of this debate.

far better to have an well-founded account rather than a miracle, despite the fact that problems were being resolved all the same. As he puts it: “[w]e do not really understand what are the truly fundamental degrees of freedom, what is the underlying dynamical principle and what are the underlying symmetries?” (ibid.). Gross further asks: “how many more string revolutions will be required before we know what string theory is?” [31, p. 104]. We haven’t moved so very far in the intervening 10 years: there has been no ‘third revolution,’ though, as with the AdS/CFT conjecture, one might consider raising the status of the Landscape conjecture to revolutionary status. However, this too is more of an aftereffect of D-branes. Still, it is an aftereffect that reinvigorated the field, coming around a decade since D-branes were understood to be a pivotal concept.[63] In its essential details, however, the landscape is a much older concept in string theory. What changed is that D-branes brought it under greater statistical control. The recent developments on the gauge/gravity duality did truly transform the state of the discipline: whatever string theory is, it’s not as it was known prior to 1994/5. Advances have been made.

Much of the most recent work (as of 2013) has been devoted to unpacking the consequences of this duality and pushing it to its limits in order to extract realistic models, instead of QCD-*like* models. With this class of dualities there has also emerged an increased inclination amongst string theorists to engage in debates on the conceptual foundations of string theory, discussing such issues as the emergence of space-time, relational locality and the nature of physical observables (much as had occurred in the mid- to late-1980s. The ability of the AdS/CFT correspondence to provide a potential resolution of the black hole information paradox, allowing unitary condensing and evaporation of black holes (by studying a dual unitary gauge model of the process) is an important event that has to play a role in how string theory is evaluated. The Landscape has blended with some of this machinery, opening up new possibilities for explaining otherwise puzzling features of our universe.

The first revolution was characterised by an obsession with replicating the standard model (especially the fermion generations). The second was concerned more with black hole physics, but also went back to its origins in strong interactions, where it attempted to answer the kinds of strongly coupled problems that other approaches found too difficult. The present era has linked up with cosmology, and is tackling the really big questions about the universe as a whole. Gross latched onto these emerging connections between string theory and other areas such as cosmology:

> Cosmology needs string theory as it tries to push back to the big bang. Inflationary theory needs string theory to justify its sometimes ad hoc or fine-tuned constructions. . . . Conversely string theory needs cosmology. String theorists hope that cosmological observations will enable one to make contact with observation [31, p. 102].

I expect that the next era will focus on pushing these connections to their limits. Solving riddles that appear to be ‘out of bounds’ appears to be a specialty of string

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[63] There appear to be roughly decadal cycles (the explosive snores of Terry Gannon’s drunk from the preface perhaps?) in which some new big idea transforms string theory: (1974: dual models of everything) → (1984: anomaly cancellation/heterotic strings/Calabi-Yaus) → (1994/5: D-branes and dualities) → (2003/4: the anthropic landscape) → (2014: ?). It seems we are due a new cycle.

theory, and cosmology has these in abundance. Absent direct experiments, such unified puzzle-solving offers a much needed alternative source of empirical support.[64]

To get a better grasp on where string theory has come from, and where it might go in the future, it is instructive to sort its evolution into stages that I will characterise as 'playing with $\mathscr{X}$' (where $\mathscr{X}$ is some particular concept or tool). Different choices for $\mathscr{X}$ will often link up in unexpected and fruitful ways, possibly triggering a new phase of development. We find, for example:

- Playing with the operator formalism.
- Playing with the string picture.
- Playing with limits:
  - zero-slope
  - large-*N*
- Playing with supersymmetry:
  - worldsheet
  - spacetime
- Playing with compactification:
  - lattices
  - winding
  - orbifolds
- Playing with duality:
  - D-branes
  - black holes
- Playing with the Landscape.

Such phases are themselves characterised by a near-exhaustive approach, examining all possible ways of using, stretching, and thinking about the $\mathscr{X}$ in question, and often mixing in ideas from other phases.[65] I have indicated some possible subdivisions one

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[64] The style of explanations given by string theory are very much on a par with those in cosmology. Consider: why do there appear to be no magnetic monopoles in the universe? This is a question concerning an empirical fact that we know (it is old evidence, if you like), but that is still in need of an explanation (especially if one believes that the universe began in an extremely hot state). Likewise, the horizon problem: why does there appear to be some kind of conspiracy linking the thermal behaviour of causally disconnected regions of the universe? No theory predicted these features *prior* to our having known about them. However, that inflationary cosmology was able to derive them as consequences (using the same mechanism) is a success of the theory, whether or not they constitute genuine predictions. It is no accident that, like string theory, cosmology often has recourse to anthropic reasoning.

[65] For example, the winding phase became a tool in the orbifold phase. The winding notion was generalised to 'wrapping' once the notion of branes came about. The wrapping and winding were used (in tandem with D-branes) to resolve a problem with stability of compact spaces, which in turn led to the Landscape (with its possibilities for doing statistics of vacua, thanks to the discreteness involved in the winding).

might make, though I'm sure many further subdivisions could be found within each of those I have suggested. I certainly don't mean to suggest that this exhausts the development of string theory. For example, missing from this idea is the analogical reasoning that has permeated all stages of string theory's evolution. In fact, it is almost *always* the case that heavy analogical reasoning is at work in the initial period of these various phases, where they are often pushed until they snap—in which case one will have learned something interesting: a breakdown of the older concepts.

The present phase appears to be based around playing with the *Landscape* and *holography*.[66] This looks set to stay for a while, but it is interesting to speculate on what the next 'playtime' might involve. In most of the cases in the past, however, the new phases have been almost entirely unexpected, which is precisely what leads to the sudden frenetic pace that follows. It is entirely possible that the phase transition will not be a new idea at all, but some confluence of pre-existing ideas (as with D-branes and dualities).

At the second Nobel Symposium in 1986, with a talk possessing the same title as my final section title, John Schwarz writes:

> I was asked recently what is the fundamental equation that we are trying to solve. I found the question somewhat awkward to answer in a few words, because while we know what we are talking about, there does not yet exist a concise and elegant description of string theory [59, p. 197].

At the very same symposium, in the closing talk, Murray Gell-Mann wrote: "there is a hint that the search for the principle underlying superstring theory may bring us back to the vicinity of where we started, the duality version of the bootstrap" [23, p. 205]. Behind this remark lurks a grain of truth: at the root of the belief that there will be a dynamical principle[67] that (non-anthropically) selects the unique configuration describing our world from a bunch of *prima facie* equally qualified configurations, is, I think, a bootstrapper's dream (or hangover). It is a desire to have the world uniquely fall out from the right consistency conditions. For better or for worse, this 'dream' has pushed string theorists on, still searching for the elusive principle while more and more structure is added and the framework is ever more radically altered. Such extra-empirical principles clearly have a role to play in theory-building. Those who adopt the anthropic stance are guided along different channels, and inevitably uncover different aspects of the same structure that is common to both camps, as well as different applications that are not common to both. It isn't at all clear which group the future development of string theory will favour. My guess is that the anthropic stance will succeed partly because it has strong support in aspects of cosmology, but also because the notion of a physical theory that uniquely pins

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[66] I'm including in this especially the utilization of infrared 'domain walls' to attempt to recover confining gauge theories which I see as conceptually continuous with the earlier constructions involving orbifolds, twisted sectors, and the like, in order to get out certain realistic features.

[67] This belief is quite clearly expressed by one of Chew's students, John Schwarz, when he writes: "There is a widespread belief, which I share, that a beautiful and profound principle lies at the heart of string theory. When elucidated, it should become much clearer why all these miracles have been turning up" [59, p. 198].

down our world seems too strange a prospect. But this is just an opinion. It is more likely that the two stances will continue in parallel, as they appear to have done for some time, defined more by the personalities of those adopting them than by the physics.

## 10.5 Closing Remarks

I hope to have revealed in this book a little more of the history of string theory than is usually presented, even in professional accounts. The lesson I think emerges from this is that, while the mythological presentations of ‘revolutions’ and ‘dark years’ and so on, make for a good story, a more accurate depiction reveals a somewhat less turbulent life story, though no less interesting for it. Though there are indeed curiosities in the history of string theory—preeminent amongst these being the phase of exaptation from hadronic to ‘fundamental’ strings—for the most part it represents a perfectly rational sequence of events, not so very different locally from any other area of physics. Indeed, I think that in presenting string theory’s historical trajectory as a somewhat quirky roller-coaster ride, the proponents of string theory might have shot themselves in the foot! Those that have not studied string theory might be far more willing to give strings a chance if they knew that perfectly ordinary quotidian principles of scientific theory construction lay at its heart. This is the story I have attempted to tell, and it is my hope that it may do a little good in taming some of the hype and hysteria forming the controversy over string theory and its elevated position in the research landscape. I might also add that throughout, the majority of those with an interest in string theory have not been irrationally convinced of its absolute certainty, but rather have seen that the potential payoff is so large that it makes the risk of its being a dead end worth taking: if one has an example of a likely-looking candidate for a unified field theory of all known interactions and elementary particles, then that is surely reason enough to pursue it.

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