9 THE CC AND THE DISCRETUUM, 1996–2000

9.1 FOLLOWING UP

So next came a lot of lectures and colloquia. D-branes were a fun story to tell: basically just systematic application of *T*-duality, and from it one gets so much, but it was all new to most people. Right after I wrote my D-brane paper, I gave a lecture series at the ITP, transcribed by Clifford Johnson and Shyamoli Chaudhuri; a few months later I gave an expanded version of this at TASI. For the colloquia, the most notable point was the duality diagram (figure 9.1). This emphasized that the five string theories and M-theory are connected, and each is the limit of the moduli space of a single quantum theory. The theories are supposed to depict dual theories close together, separated alternately by *S* and *T* dualities. But I somehow switched the two heterotic theories, both in the colloquia and in my book.[1]

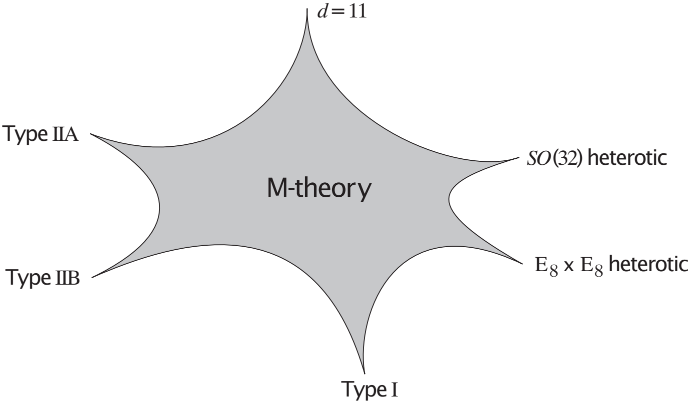


Figure 9.1
The duality diagram, with $SO(32)$ and $E_8 \times E_8$ accidentally transposed. Correctly drawn, the edges alternate between S-dualities and T-dualities.

So, what to work on next? Looking at INSPIRE, I see that my next three papers, besides the reviews, were about orientifolds and K3s. This is more geometric than I would normally like, but orientifolds were a bit of fun that was richer than D-branes alone. And K3s, the simplest Calabi-Yau manifolds, had an orbifold limit that satisfied my preference for no curvature. So Gimon and I finished his paper, which was rather more extensive than when it began before D-branes.[2] Berkooz, Leigh, Schwarz, Seiberg, Witten, and I made a study of six-dimensional K3 solutions that I think began as a collaboration with Edward and then grew when other groups were working on the same problems. My last paper was single-author again about K3 puzzles, which I liked because I got to use an idea of Michael Douglas of using D-branes as probes.

Strings '96 was held at Santa Barbara. Strominger had said to me a year earlier, "We should run Strings next year," by which he meant "Joe, you should run Strings next year." My light teaching load made it hard to object, though I have never been a good organizer. But with the ITP postdocs (Shyamoli Chaudhuri, Clifford Johnson, and Katrin Becker) and especially the excellent ITP staff, it went well. But I was not happy with my own talk. I felt that I should have some ringing program for the future, after my world-changing paper of eight months earlier, but all I had was some subtle inconsistencies of certain orientifolds.

I recall two notable events from the meeting. The first was an email signed Steven Hawking, with the title "I Have Changed My Mind. Information Is Not Lost." But this was a spoof, and soon we heard from the real Hawking, with the title "Why I Have Not Changed My Mind." The second event was the announcement of matrix theory, by Banks, Fischler, Shenker, and Susskind.

9.2 REVOLUTIONS THREE AND FOUR

Almost immediately after my D-brane paper, Strominger came to me excited that he would be able to calculate the microscopic density of states of black holes. Having learned GR from Weinberg, I had not given this question much thought, but Strominger, a more gravitational physicist, told me that this was just as important as the information problem. His calculation was just off by a constant, and he was looking for help. This was all too new to me, and I had nothing to contribute. But he found Vafa, who had the right tools, and they got the first precise counting of black hole states. They had connected string theory to a new aspect of quantum gravity.

Gary Horowitz also had a long-standing interest in the black hole entropy. He kept coming back to the question, how do we count the states for ordinary Schwarzschild black holes, not just the highly supersymmetric Strominger-Vafa black holes? We could not get as sharp an answer as SV, but we did get a crude but useful result, extending an idea of Susskind. Imagine turning

BLACK HOLE MICROSTATE COUNTING

One of the most mysterious aspects of a black hole is its similarity with a hot box of gas. It has an associated temperature and *thermodynamic entropy*—a notion quantifying the ignorance of the particular state of a system—that are encoded geometrically in the shape of the spacetime around it. Its entropy is given by the *Bekenstein-Hawking* (BH) formula as the area of its event horizon as measured in Planck units. For a black hole of a given mass, charge, and angular momentum, this suggests that the number of distinct configurations or microstates of a black hole is equal to the exponential of the BH entropy. However, a black hole spacetime does not have any obvious structure able to account for this many microstates.

Black hole entropy

$$S_{\mathrm{BH}} = \frac{\mathrm{Area}}{4G_N}$$

Figure 9.1a

The missing structure emerges in string theory as none other than Joe's D-branes. This has allowed for a precise counting of microstates in a class of supersymmetric black branes in accordance with the BH formula. By tuning the strength of the gravitational force through adjusting the value of the string coupling, one is able to interpolate between a stack of D-branes at weak coupling and a black brane at strong coupling—the D-branes collapse into the black brane once the gravitational force is sufficiently strong. The upshot is that the counting is simple using the D-brane description at weak coupling, and supersymmetry ensures that it remains accurate even at strong coupling. The result is that the number of configurations of the stack of D-branes is precisely equal to the exponential of the BH entropy of the black brane.

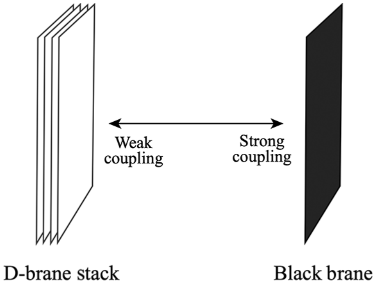


Figure 9.1b

down the string coupling for a black hole. The black hole gets smaller, and eventually reaches the string length. At that point, one should match the black hole density of states to that of the weakly coupled D-branes and strings. This gave a correspondence principle, matching the approximate counting for various black holes. In a follow-up we studied the transitions of long strings to black holes.

After the successes of black hole state counting, it was natural to think about comparing the dynamics of black holes and D-branes, with an eye on understanding Hawking radiation and eventually information. Douglas, Strominger, and I, working at Aspen, studied branes as dynamical probes, interacting with clumps of D-branes and also with the dual black hole. These agreed up to one loop, a dynamical correspondence between D-branes and black holes. At two loops they disagreed. We looked for many solutions to this, but I think in the end we must have been calculating a quantity that was BPS only up to one loop, an issue that was confusing in the early days of duality. In any event, the comparison of the dynamics of D-branes and black holes became an active issue around then, and the unexpected agreements between the two sides was one of the clues that led Maldacena to AdS/CFT.

The BFSS matrix model, presented at Strings '96, was fascinating. It combined D-branes, eleven-dimensional supergravity, and matrix models into what was argued to be a complete description of M-theory, the mysterious theory that lived in eleven dimensions and was dual to string theory. There was, at the time, a bit of confusion about what this meant. Now we would understand it as a duality, two distinct descriptions of the same theory that are weakly coupled in distinct regimes. But the way the theory was presented, many of us interpreted it more as a weak-weak duality, where one obtained the dual gravitational interaction from an explicit calculation in the matrix theory.

Thus it was interesting to see how far the calculations of BFSS could be taken. The BFSS construction treated the longitudinal and transverse directions differently, but they had to combine in a Lorentz invariant way. The initial calculations of graviton scattering were all for transverse momenta. Longitudinal processes were harder, involving instantons rather than loops in the matrix theory. But we had a new postdoc, Philippe Pouliot, who had some experience with instantons, and together we found that the instanton matched the longitudinal process. This was fun for me, my first detailed instanton calculation, and a foothold into M-theory.

Two other postdocs, the sisters Katrin and Melanie Becker, were also extending the BFSS calculations, from one loop to two. It was the kind of hard calculation that they enjoyed. Arkady Tseytlin and I joined in to understand how the result should match on to the gravitational theory. We found that again they matched.

The BFSS theory was unusual in several ways, one of which was the need for infinite-dimensional matrices. Susskind argued that even for matrices of finite-dimensional *N*, there was a physical interpretation of the theory and its dual. The longitudinal direction becomes periodic, with quantized charge *N*. This was an interesting quantum system, a periodic null direction, and with my second UCSB student, Simeon Hellerman, we unraveled some of its subtleties. I would have liked to take these subjects further, but other obligations intervened.

I see the second superstring revolution as five waves in succession: the first four were Witten's Strings talk (and the preceding Hull-Townsend paper), D-branes, the SV black hole counting, and the BFSS matrix model. AdS/CFT would be the fifth and crowning glory. Each built on the ones before it, and each greatly expanded our understanding of string theory.

9.3 CH-CH-CHANGES

I had taken a year off from the book, but it had reached the point where I had to finish, no matter what. And so I resolved to do nothing else until I was done. People tell me that I was a zombie during this period, that they knew that there was no point in trying to talk to me.

To give myself discipline, I kept track of the number of pages I wrote each day. The list has been tacked to my office bulletin board for twenty years, but I had not looked at it in that time, until writing this chapter. When I did I was stunned. In nine years, I had written what is now volume 1, less than half the present book. This is consistent with Candelas's maxim; it is never too late to give up on a book. And I think I would have, if I had not told everyone that I was writing it. At least the superstring revolution did not make things a lot worse. There was a chapter on superstring duality, and one on D-branes, but after giving colloquia and lectures these were easy to write. Then there was just a section each for black hole entropy and on matrix theory, just to give an idea, and a paragraph on AdS/CFT, which just made the deadline.

One reason for the time spent on volume 1 was that I rewrote the first few chapters several times. I reduced the amount about BRST symmetry, which had seemed like it might be the key principle at the beginning, and correspondingly I added to the conformal field theory section. I had the idea that I would write a book so clear that a student would pick it up one night, be unable to put it down, and in the morning they would know string theory. I never got it to a point that satisfied me, but people seem to find it useful.

According to my tally, it took 83 days of writing, spread over six months, to produce the five-hundred-page volume 2: a little over three days per week for six months. This does not include the time spent researching the many subjects in the book, most of which I had not worked on myself. There were also three short breaks, to finish the papers with Becker, Becker, and Tseytlin, with Horowitz, and with Hellerman. I had some life: the record shows a four-day family trip to the sequoia forest and the Kern River, and I continued to coach my sons' hockey teams. But I am sure that I was usually a zombie.

The decision to split the book in two came during this period, when the length became clear. The overall title, simply "String Theory," had been in place for a long time. Initially, I had used "A Modern Introduction to String Theory," signifying the use of the Polyakov description, but I realized how quickly such a title could look dated. Though if I were to write it today, it is not obvious how else to start. I also started using "Joe's Big Book of String" as an informal title very early; I should have fought harder to make this the official title.[3]

And after the writing, there was another six months of drudgery: proofreading, checking equations, designing exercises, making copyeditor's corrections, writing a glossary, references, and an index. And at each step I had to go through all eight hundred pages. The index at least was fun. There is a right way to do an index, which is to go over each page and see if there is anything on the page that a reader would need to find. But finally I was done.

I had fallen short on my easy-reading goal, and I also fell short on my goal of no typos. I had gone through every equation, but I have to face the fact that being detail oriented is not one of my strengths. And it is especially hard to keep consistent notation on an 800-page book with many interlocking subjects. So there are now more than 400 errata, at least 200 coming from Bank's then-student Lubos Motl.

Finally, I had planned to include a proof of the finiteness of superstring theory. I think I had done a good job explaining why the bosonic string is finite, modulo the tachyon. But there was no proof in the literature, and after a few attempts I realized that it was beyond me in any reasonable time. Indeed, this was done only recently, by Witten, in several long papers.

Earlier I mentioned heavy quark theory as a missed opportunity from working on my book. A second one was the chance to work more with Simeon Hellerman. He was an outstanding student, with a unique approach to life (for example, his current seminars consist of 3,000 slides, shown in stop motion). We wrote two papers getting into matrix theory, but then I had to go into zombie mode for a year at a key time for him. He wrote two nice papers with Sean Carroll (then an ITP postdoc) and Mark Trodden on domain walls. He then went on to postdocs at SLAC/Stanford and the IAS and then a faculty position at IPMU in Tokyo, writing novel papers all the way.[4]

I don't recall any particular celebration, just a chance to get back to work and catch up with all the latest excitement. The royalties started coming in, which was a nice bonus but of course not the reason I wrote the book. Years before, David Jackson had a party, and showed us the house in the Berkeley hills that his E&M book had paid for. Some time later, in Florida, Pierre Ramond showed me the nice telescope that he had bought with the royalties of his quantum field theory book. Well, over time, my book paid for a BMW, including taxes: the root mean square of the house and the telescope.

So freedom from the book was the first big change. At about the same time, David Gross arrived to become the new ITP director, the second big change. After Kohn's five years, and Schrieffer's five years, Jim Langer had stayed for seven years to try to find his successor, and then Jim Hartle became interim director and continued the search. Their patience was rewarded when David Gross accepted.

I had not known Gross very well before, but his reputation as a force of nature was quickly justified. The ITP had been running in its original mode for nineteen years, and was still regarded as a model for the world. But there was a need for renewal, and Gross came in with a bang. Right from the start there were changes. An espresso maker was the first symbolic step, but then there were new programs for graduate students, physicists doing research at universities with heavy teaching loads, high school teachers, artists, and journalists, and new or expanded areas of science such as biophysics, mathematical physics, and geophysics.

Most significantly, he reorganized the programs. These had been running on the same 2 × 2 × 5-month annual schedule since the beginning. But the new building was not being fully utilized. Also, it did not make sense that every program should have the same length: some fields and subfields are bigger than others. And changes in families and universities made the idealized five-month stay impractical. So programs became 50 percent larger, but with variable length. It took a while to convince the staff, some had spent years with the old system, but Gross got his way. And we still had Boris Kayser at the NSF to help fund the expansion (but never enough with the NSF). So there was a new feeling of excitement.

The third big change was Strominger moving to Harvard (where his father taught chemistry).[5] The second superstring revolution had set off a wave of reshuffling. Departments could tell that there was something exciting going on, even if they were not sure what it was. And a large backlog of excellent grad students got jobs.

9.4 ADS/CFT

While I was finishing the book, the fifth wave of the revolution struck, AdS/CFT. But I was in the perfect place. A program, "Dualities in String Theory," was scheduled for January to June, 1998, and Maldacena's paper appeared just a month before. Moreover, he was attending the program and spoke about his work in the second week. Neither the paper nor the talk produced an immediate sensation. It was too new. We had internalized field-field dualities, and string-string dualities, but string-field dualities? How could the degrees of freedom match?

So, like many, I went through the Kubler-Ross stages for dualities: disbelief, contradiction, testing, and acceptance. The immediate contradiction was that string theory had many more degrees of freedom than field theory. But the large N of the field theory made many things possible. More specifically, it seemed that one could find nonsupersymmetric string states that had no analog in the field theory. But a closer look identified them as bound states. And after a few such checks, duality became the simplest explanation for what was happening. Having come to this point of view, it bothered me that for a long time people would say that AdS/CFT is just a conjecture, rather than a duality. Of course, dualities are almost all conjectures, but *duality* indicates the further tests above. And AdS/CFT was rapidly subjected to an enormous number of tests, without contradiction.

ADS/CFT

The *holographic principle* is perhaps one of the deepest insights to emerge from black hole physics. Motivated by the Bekenstein-Hawking entropy formula, it states that the total amount of information inside any region is bounded by the area of its surrounding surface. Squeezing in additional information would trigger the region to collapse into a black hole. String theory provides the most precise realization of this principle in the AdS/CFT duality, stating that a gravitational theory inside a $d+1$-dimensional AdS spacetime is equivalent to a nongravitational QFT restricted to its d-dimensional boundary.

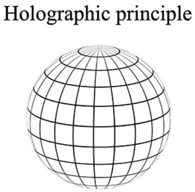


Figure 9.1c

The discovery of AdS/CFT was fueled by D-branes. The strategy was to equate two different descriptions of a stack of D-branes obtained by starting at weak coupling and then taking the limits of strong coupling and low energy in the two possible orders. Taking the strong coupling limit first causes the stack to collapse into a black brane. The low energy limit taken next focuses on its near horizon region, which is described by string theory in AdS. When the low energy limit is taken first, the open strings on the stack decouple entirely from the surrounding spacetime, and are described by a weakly coupled CFT. Then, taking the strong coupling limit of this CFT would close the loop and give an alternative description of string theory in AdS that was obtained in the first order of limits.

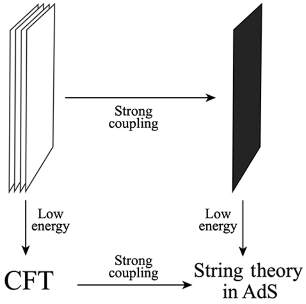


Figure 9.1d

This duality is often illustrated using a *can of soup picture*, where the *soup* is the AdS spacetime—it's noodle soup because, well, strings—and the *can* is the CFT on the boundary. Time runs upward along the can. The AdS spacetime is often referred to as the *bulk*, and the CFT as the *boundary* theory.

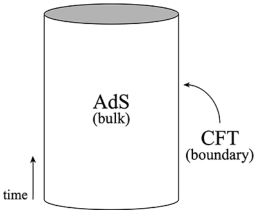


Figure 9.1e

I got a slow start on AdS/CFT while I finished my book. But I was used to that. I usually went into a new area slowly, while I tried to understand what was really going on. For this reason, I have rarely had to worry about being scooped; if someone else can solve the problem, I am not needed.

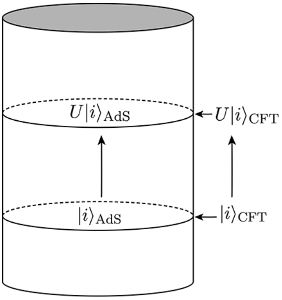
With AdS/CFT there was a UV/IR connection, where the AdS radial coordinate scaled as the energy of the CFT. What puzzled me and postdoc Amanda Peet was that different arguments gave different powers of the string coupling g_s in the AdS-distance/CFT-energy relation. What we realized was that the different relations came from using different probes, with different masses. If the probes were labeled by their size rather than their energy, then the AdS/CFT relation became uniform. So it was a size-inverse size relation, rather than size-energy.

The next exercise was to obtain the flat spacetime S-matrix as a limit of the AdS S-matrix. This was a straightforward limiting process, though it required a non-'t Hooftian large-*N* limit. Coincidentally, Susskind published the same result on the same day, though I think that his had a broader scope.

This got us talking about AdS/CFT, and he told me about a paradox he was puzzling over. If one has a quantum scattering at the center of AdS, the energy density at the boundary cannot change before a light-travel time. But at that time it has to change instantaneously to a new distribution. This seems acausal, but it is not; it is perfectly consistent with quantum field theory. So we analyzed the bulk and boundary causality, introducing *precursor* for boundary operators that represent bulk states in the interior, a term that is in wide use now. But the idea went back to the year before, to Banks, Douglas, Horowitz, and Martinec (BDHM) and to Balasubramanian, Kraus, Lawrence, and Trivedi (BKLT).[6]

PHYSICS OF ADS/CFT

The AdS/CFT duality comes with a *dictionary* that relates the physics of the bulk to that of the boundary. It includes a one-to-one mapping between their quantum states, as well as their time evolutions.



Bulk-boundary map

$$|i\rangle_{\text{AdS}} \cong |i\rangle_{\text{CFT}}$$

Figure 9.1f

The simplest entry of this dictionary is that empty AdS spacetime is dual to the vacuum state of the CFT. Another is that a bulk state with a particle near the AdS boundary is dual to the excited state of the CFT created by the action of a local field on the vacuum state. Under the identification of the bulk and boundary time evolutions, time evolving the local CFT field corresponds to the near-boundary particle simply falling in. This defines the *precursor,* the time-evolved local boundary field dual to the particle deep in the bulk.

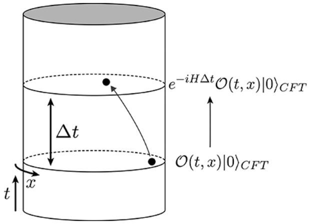


Figure 9.1g

While the bulk evolution is simple, the evolution on the boundary CFT is complicated due to strong coupling. The local excitation in the CFT interacts strongly with nearby degrees of freedom, causing the excitation to grow with time. This establishes a connection between the size of the excitation on the boundary and how far the bulk particle has fallen in.

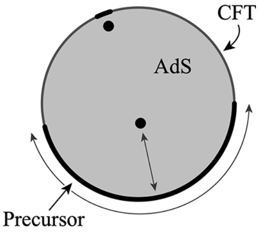


Figure 9.1h

9.5 STRASSLER

One of the great experiences I had at the ITP was having a visitor come into my office, explain to me the solution to an important problem, and ask me to help them work it out.

But first some backstory. Kallosh and Linde (KL) had found new solutions to supergravity. These had negative energy singularities and repelled massive objects, so KL named them *repulsons*. Postdocs Peet and Johnson and I, with the aid of AdS/CFT, deduced that the singularity should expand into a nonsingular shell of branes. This was a satisfying result, and allowed me to tell relativists that the reason they could not resolve the repulson problem was because they didn't have enough branes. We named this shell an *enhaćon*, for its enhanced gauge symmetry.

So Matt Strassler came into my office with a singularity that he needed resolved. He was interested in four-dimensional AdS duals to confining theories. These could readily be obtained by giving masses to some or all of the CFT scalars, leading to $N=0$, 1, or 2 SUSY; he called these 0*, 1*, and 2* SUSY QCD. The problem was that these seemed to lead to singular solutions, whose properties could not be calculated. Strassler thought that the same ideas that had worked for the repulson might work here as well.

In fact, he recognized the key idea even before he spoke with me: the D3-branes blew up into D5-branes by a beautiful mechanism that had been discovered by Rob Myers. So Strassler had a rather complete picture of both sides of the duality even when he first came into my office. For example, he knew that there would have to be NS-5 branes, and bound states, as well. My main contribution was to identify a small parameter, $g_s N/n^2$, where n was the number of probe branes, that allowed calculations. In the end it was a nice picture, with a lot of physics in it. It was also a very long paper, which has never been published. Strassler is a perfectionist, and we got stuck on one thing, getting the $U(1)$ gauge factor straight. Impressively, in the same year he found a completely different solution to a very similar problem. With Klebanov, he found a solution that was purely geometric, without brane sources.

SINGULARITY RESOLUTION

General relativity predicts its own failure through the formation of spacetime *singularities*. These are regions of spacetime, most famously inside black holes, where Einstein's equation breaks down due to the uncontrollably large curvature. A putative fundamental theory from which GR would descend must have the ability to resolve these singularities and shed light on their properties.

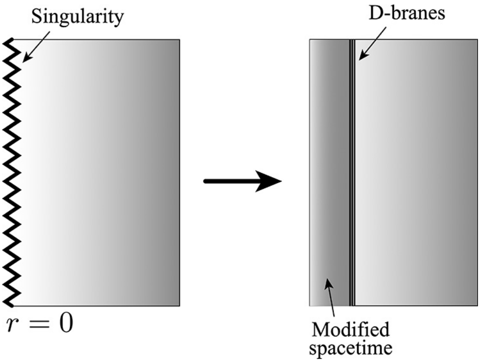


Figure 9.1i

String theory is our leading candidate for such a fundamental theory. It successfully resolves some singularities by appealing to a more refined structure of spacetime, much in the same way that divergences in QFT are resolved by refining point particles into tiny strings. In AdS spacetimes that emerge from a stack of D-branes, certain naive singularities are precluded by the reemergence of those D-branes near the would-be singularity, and replacing it with a smooth spacetime.

I was pleased to have several more opportunities to work with Strassler; the combination of our different points of view was productive. One project began from my memory from SLAC, of Stan Brodsky's work on hard scattering, where all the constituents of a hadron scatter together: it is suppressed, but still power law in field theory. Could AdS/CFT reproduce this? Normally, one would expect soft scattering in the string description, but the warping of space converted this to the power law of the field theory. Because our first paper had run so long, I insisted that we publish in *Physics Letters*, with its four-page limit, but it still took a while.

We then extended this to deep inelastic scattering, scattering a hard probe against a hadron. This was the basic process by which the internal properties of hadrons were seen. Of course, strings had a very different internal structure, and correspondingly the scattering was very different. Between weak and strong gauge coupling there was a transition from the operator product dominated by parton operators to one dominated by hadrons. I had heard about these things in the early days of QCD. Now we could have our own toy with AdS/CFT, and understand what was the same and what was different.

Our last project, a few years later, was understanding the Regge behavior, $s^{\alpha(t)}$ at large s and fixed t. In flat-space string scattering, the Regge trajectory $\alpha(t)$ is linear in t. Many years earlier, Charles Thorn had told me that in QCD, the trajectory is linear in the timelike region of t negative, but then bends over toward a constant at spacelike t. These two regions were referred to as the soft and hard (or BFKL) *pomerons*. So my motivation was to understand this in AdS/CFT. The other collaborators, now including Rich Brower and Chung-I Tan, may have had other motivations. And it worked nicely, thanks to the warping. The soft pomeron came from the IR region of AdS, and the hard pomeron came from the UV region. So once again AdS/CFT gave a nice way to think about QCD physics.

I also had a nice but little-known follow-up with Susskind. He wanted to understand how the string dual of a gauge theory could have local currents, which are impossible in normal string theories. This discussion came up when we were both at the 60th birthday celebration for John Schwarz, and we solved it there. As with many aspects of nonconformal field theory duals, it was the warping of the bulk that was responsible. But I most remember a bit of grandstanding by Susskind, who asked Mimi Schwarz (John's mother, and not a scientist) to adjudicate an issue in the discussion. He was making the point (convincingly) that the issue was so clear that he could explain it to Mimi. So we added her name to the acknowledgments.

9.6 BOUSSO

In 1998, strong evidence was found for a cosmological constant, surprising almost every theorist. One might have expected string theorists to drop everything and think about this, but there was little reaction. Certainly, a large part of this was that AdS/CFT had just been found, transforming fundamental theory. We needed to understand the theory better before applying it.

My own reaction was different, from my interactions with Weinberg. I had half-expected the CC, and had feared it. Indeed, when the evidence started to come in, I told our postdoc, Sean Carroll, that if the CC turned out to be there, he could have my office. It would mean that the anthropic principle was here, and I would have to give up physics. I make a lot of comments like this that I do not remember—unfortunate, otherwise this memoir would be funnier. But Sean remembered, and as he introduced me at a meeting two years later, he asked when he was going to get the office.

Others were also unsurprised, including Linde, Kallosh, Susskind, Banks, Bousso, Silverstein, and Kachru. Notably, these were all on the West Coast. It was a new version of the East Coast/West Coast divide. Those on the East expected an elegant theory, with vanishing cosmological constant and perhaps even a unique ground state; perhaps some small effect would explain away the CC. Those on the West Coast were not so caught up in these myths, though I would prefer if they were true.[7]

I thought it might be a good idea to see whether string theory had the right microphysics to allow Weinberg's solution, but I put it off. Then Raphael Bousso, a former student of Hawking, now a postdoc at Stanford, came to town. He was interested in the same question, and goaded me to think about it with him. First, it was clear that the old idea of Hawking, Duff-van Nieuwenhuizen, and Aurilia-Nicolai-Townsend of a continuously variable four-form potential could not work in string theory. In string theory, the forms are the charges of space-filling D-branes and so are quantized. The old ideas of Abbott and Brown-Teitelboim used discrete charges, but they needed implausibly small quanta and large charges, 10^{60} with SUSY and 10^{120} without, to get a small enough CC. And they did not have a mechanism to get matter.

Bousso and I realized that in string theory there were typically multiple fluxes, which could be incommensurate depending on the topologies. In this way, much smaller individual charges could combine in many ways. With one hundred fluxes, a typical number for a Calabi-Yau compactification, charges of order 10 would give us 10^{100} states. This produced a spectrum much more disordered than the single-flux case, which we named a *discretuum* to contrast with *continuum*. With large compact dimensions, as few as four fluxes might work in large-dimension models.

Figure 9.2
Joe and Stephen Hawking in Cambridge, 2001

Most of this came from one or two conversations. But when Bousso came back a few months later, he had a complete draft. He had added an important part of the story, the cosmology that allowed the theory to explore all these states. It was just Linde's eternal chaotic inflation: given any de Sitter state, all the rest would eventually be produced by expansion and tunneling. I had always assumed that such a thing would not be part of string theory, but in fact it arose quite naturally.

DISCRETUUM

Solving the cosmological constant problem requires finding a natural mechanism that can transform a large *bare* CC, say, at the Planck scale from quantum loops, down to the small observed value. A mechanism that string theory provides is to modulate the CC using electromagnetic (EM) energy that can be sourced discretely by D-branes and other charged membranes. Having many such membranes with incommensurate charges produces an extremely fine discrete range of CCs, an almost continuum, giving a *discretuum* of possibilities as a function of the number of membranes. What remains is to find a mechanism that explores this discretuum and that would eventually land on something like our observed CC.

$$S = \int \sqrt{g}\left(R - \underbrace{\overset{\substack{\text{CC}\\ \downarrow}}{\Lambda_0} - \sum_{i=1}^{N} \overset{\substack{\text{E\&M}\\ \downarrow}}{F_i^2}}_{\Lambda_{\text{eff}} = \Lambda_0 + \sum_{i=1}^{N} n_i q_i^2}\right)$$

Figure 9.2a

This exploration can be achieved using quantum tunneling between different numbers of membranes. The idea is to start with a universe in the far past with a large positive total CC equal to the sum of a negative bare term plus a larger positive EM energy contribution from a large number of membranes. The path toward a small CC would be to wait for the membranes to sequentially decay via quantum tunneling, producing *bubble universes* of smaller and smaller net values for the CC. If the steps in the discretuum are approximately equal to the observed value or smaller, then this decay sequence would naturally contain a descendant bubble universe with a CC consistent with our observed value. Interestingly, this model facilitates an anthropic explanation for the observed CC: only in those bubble universes with a small enough CC to harbor intelligent life would there be someone to observe it.

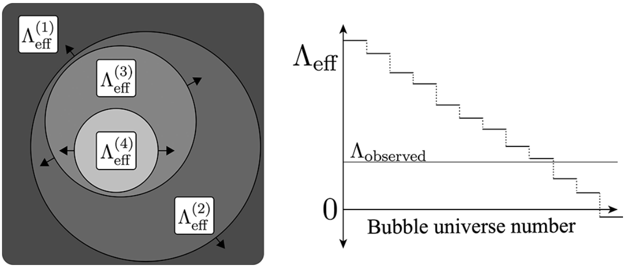


Figure 9.2b

Of course, at the time we wrote our paper, no de Sitter solutions were known, we were just working with a simplified model. But this was a natural consequence of string theorists starting with the simplest SUSY solutions, which have negative CC, and working toward the more generic ones. Now that the second superstring revolution had given us a more complete picture of the theory, young West Coast theorists would soon fill in this gap. For a while, there was lore that string theory only allowed negative CC, but not on the West Coast.

Bousso's draft had one more important point. As discussed earlier, many ideas for a vanishing CC led to a spacetime without matter. But for his (and Linde's) picture this was no problem. Tunneling could readily produce excited states of the inflationary potential, which would then decay to ordinary matter in the usual way. So, with a few details soon to be filled in, string theory produced the small nonzero cosmological constant seen in nature.

It was great being at the ITP. In quick succession, two outstanding young people brought me important ideas and asked me to work with them. And each was perfectly complementary: Strassler's particle physics and field theory, Bousso's relativity and cosmology, and my string theory. Indeed, it was an embarrassment of riches. Bousso came in with his draft a few weeks after Strassler came in with his idea. I knew that I could not work on two such intense projects at the same time, so Bousso had to wait for what turned out to be a couple of months.

Even worse for Bousso was my aversion to any mention of the anthropic principle. By the end it was down to one mention in the introduction, and one in the final paragraph. Even to get me to sign for this much was difficult, but he had a trump card. We had just offered him a senior postdoctoral position at ITP, and he said that he would accept only if I agreed to be on the paper. If not for my obstruction, the paper would have looked much more like the later and more open treatment by Susskind.

It was not that Bousso and I disagreed in any way about the physics. Just the opposite: I thought the anthropic interpretation was so compelling that even experimentalists would realize that they were measuring random numbers and be discouraged. I did not want to be the cause of that. But of course I overestimated both the credence that experimentalists gave to theorists, and the ability to make progress even with such obstacles. As Bousso and Susskind both knew, it is wrong to suppress what you know. Georgi again: "Do not hide your light under a bushel basket." As far as I know, this is the first paper written about string theory and the anthropic principle, a real illustration of the power of anthropic denial.

Notes

1. At Fermilab, someone in the audience, presumably a hunter, said that the diagram looked like a deerskin, so I always think of it as the deerskin diagram.

2. Gimon also had two nice papers on this subject with Clifford Johnson. He went on to postdocs at Caltech, Princeton, and Berkeley, writing quite a few nice papers. He now works on energy policy, sustainability, and philanthropy.

3. [Nothing stopped Joe from using the diminutive version of this title for his string theory lecture notes: “Joe’s Little Book of String.”—Ed.]

4. Hellerman was the kind of wiseacre who would tell me that going to Stanford was a step up for him. And I was the kind of wiseacre who would respond, “Yes, and I’m the one who had to lie to get you in there.” It was a comeback worthy of Sidney Coleman.

5. I have to confess that at all my stops I have had the good fortune to be associated with someone of vision—Weinberg, Strominger, Gross—because that is a quality that I do not believe I could learn. So trading Gross for Strominger satisfied my personal conservation law.

6. The initial paper with Susskind was withdrawn, and a longer paper that included Susskind’s student Nicolaos Toumbas among the authors was submitted. There was nothing wrong with the original draft; Susskind just wanted to submit an expanded explanation.

7. David Gross, having moved from East to West just at this time, was in an odd state: he knew the truth, but could only speak it when pretending to be someone else.

Memories of a Theoretical Physicist

A Journey across the Landscape of Strings, Black Holes, and the Multiverse

By: Joseph Polchinski

Edited by: Ahmed Almheiri

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