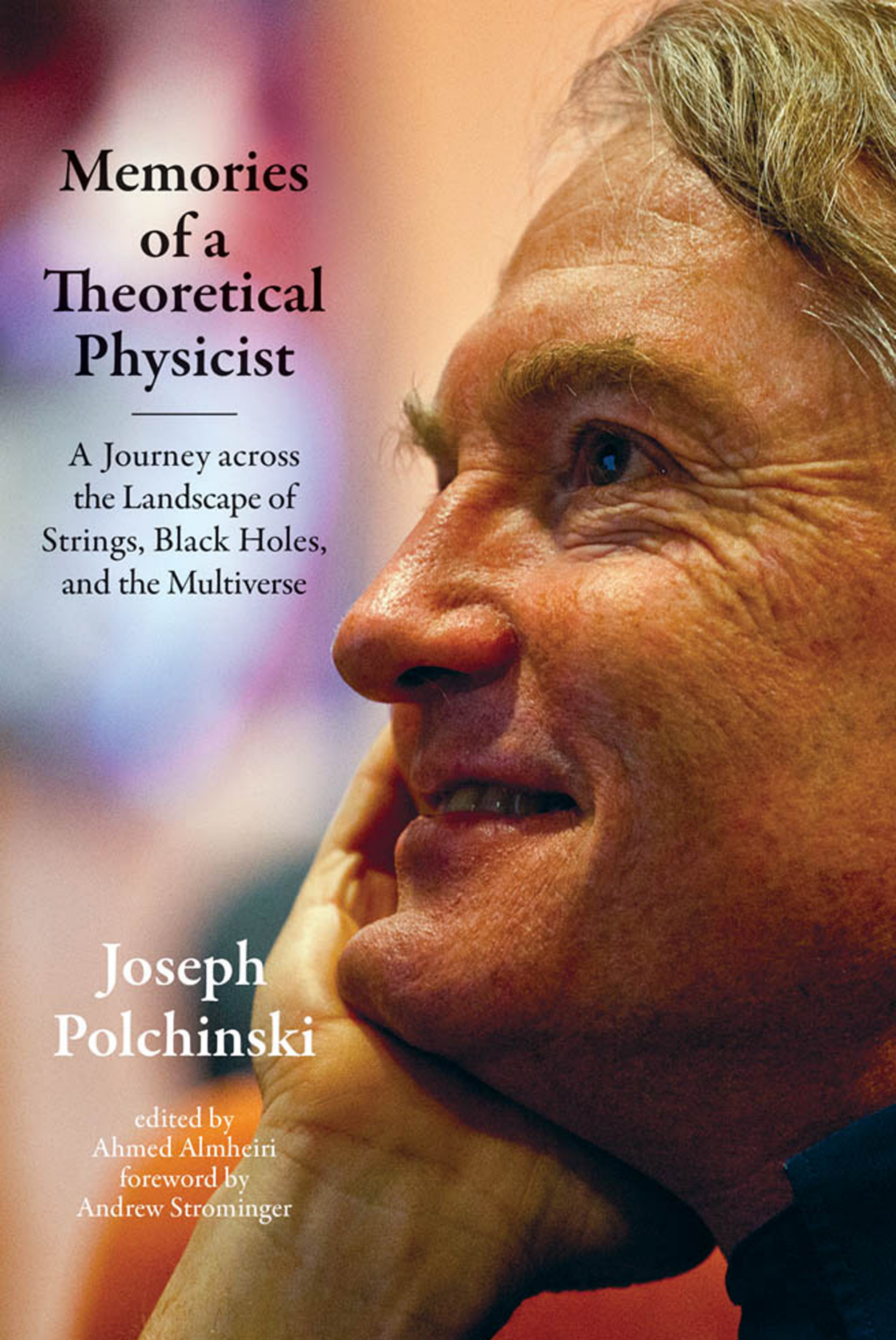

Memories of a Theoretical Physicist

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

Joseph Polchinski

edited by Ahmed Almheiri
foreword by Andrew Strominger

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The MIT Press
Cambridge, Massachusetts
London, England

The MIT Press would like to thank the anonymous peer reviewers who provided comments on drafts of this book. The generous work of academic experts is essential for establishing the authority and quality of our publications. We acknowledge with gratitude the contributions of these otherwise uncredited readers.

This book was set in Scala by Westchester Publishing Services.

Library of Congress Cataloging-in-Publication Data

Names: Polchinski, Joseph Gerard, author. | Almheiri, Ahmed, editor.
Title: Memories of a theoretical physicist : a journey across the landscape of strings, black holes, and the multiverse / Joseph Polchinski ; edited by Ahmed Almheiri ; foreword by Andrew Strominger.
Description: Cambridge, Massachusetts : The MIT Press, [2022] | Includes bibliographical references and index.
Identifiers: LCCN 2021013273 | ISBN 9780262543446 (paperback)
Subjects: LCSH: Polchinski, Joseph Gerard. | Physicists—Biography. | Physics—Philosophy. | Cosmology.
Classification: LCC QC15 .P65 2022 | DDC 530.092 [B]—dc23
LC record available at https://lccn.loc.gov/2021013273

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FOREWORD

The pages before you contain the personal chronicles of a great explorer, Joseph (Joe) Polchinski. His frontier was the most challenging of all: human knowledge. Over decades of exploration, he pushed back the limits of our understanding of the beautiful and often-surprising physical world around us. This memoir gives a firsthand account of his epic adventure from his early days as an intrepid and sometimes frustrated novice to his later enthralling glimpses into the land beyond general relativity, particle physics, and quantum mechanics.

There were no maps available for Joe's explorations, but he had his extraordinary intellect for a guide. As a colleague once put it, "Joe's brain is a national treasure."

Still, famed physicist J. D. Jackson admonished him as a Berkeley graduate student: "It's not enough to be smart." This book contains a frank and inspiring account of Joe's determined struggle, and ultimate victory over his personal impediments as a scientific explorer. Primary among them were his shyness, which made self-display and collaborative work more difficult than they are for most, and his fondness for the clarification and dissemination of others' ideas—an important pedagogical undertaking, but one that delayed him in venturing out on his own scientific path. Joe writes, "You could say that at the age of forty I had not lived up to my potential." Eventually overcoming these impediments, Joe's discovery of D-branes changed the course of modern theoretical physics and that of string theory in particular. His life path and its detours are painted for us here with fresh and lively colors through personal and professional anecdotes, all told with Joe's inimitable sense of humor.

This memoir is all the more remarkable for the manner and the conditions under which it was written. In the fall of 2015, Joe was speaking at a conference in Berlin commemorating the one-hundredth anniversary of Einstein's general theory of relativity. At this conference he suffered his first seizures and was diagnosed with terminal brain cancer. Back in California Joe underwent surgery to remove the tumor, followed by multiple courses of radiation and chemotherapy. It was then that he started writing this memoir. His brain was so ravaged by the cancer that he couldn't read or write and had to dictate the text. Yet the narrative preserves perfect accuracy and perfect chronological order in its account of events; its physics arguments are nuanced and its counterarguments precise; and the verbatim quotes from colleagues are meticulously exact, even if they date some forty years back. Evidently, his travels through physics were embedded so deep in his mind that no surgery or chemicals could remove them.

Modesty led Joe to omissions in the text, primarily in what concerns Joe's own contributions to the field, his seminal discoveries, and accounts of the generous help he offered others. I should here perhaps compensate for these intended oversights and give Joe his due.

Joe's grasp of physics was both broad and deep. He was open to all ideas and listened carefully to everyone, no matter their background, but he never agreed to anything until he understood it fully for himself. He thus became a kind of arbiter of truth in the field. I regularly brought my own ideas to him when trying to assess their viability, and there was often a line outside his door of others seeking to do the same. In the place of that line is now a hole which has not been filled. Indeed, it takes a combination of humility, attentiveness, commitment—and a very fast brain to boot—to provide such service for the field.

His contributions were duly recognized by numerous prizes, including the Dannie Heinemann Prize from the American Physics Society, the Dirac Prize from the International Center for Theoretical Physics, the Physics Frontier Prize, and the Fundamental Physics Breakthrough Prize.

Joe was renowned for his ability to provide conceptually lucid scientific descriptions, which dispensed with the inessential and rendered the subject matter clear and precise. A famous example is his two-volume tome, *String Theory*, which has become the standard textbook of the field and has sold many times more copies than there are string theorists on the planet. This memoir is replete with lucid descriptions of the exciting science encountered on his life path. Scholars of string theory will surely delight in these reflections.

On the personal side, I am fortunate to have known Joe well both as a friend and as a scientific colleague for most of our lives. We met as beginning graduate students at Berkeley, while trying to shape our then-nascent life's work. Nearly forty years later, we received the Breakthrough Prize together while our children cheered us from the back of the hall. In between were wonderful adventures and exciting scientific exchanges on hikes and bike rides, at home or abroad, in some exotic location or other, between meetings, conferences, and other occasional fun.

Our discussions about the still-unresolved but now, as a result of Joe's contributions, much-better-understood black hole information paradox continued unabated for decades. Over the course of these discussions both of us changed our viewpoint on the paradox multiple times. More such changes are likely in store for me, sadly without Joe's help. We were lifetime co-explorers of the laws of the physical universe. It was a binding and rewarding experience unlike any other.

My most vivid memories of Joe are the hundreds of lunches we used to have at the UCSB cafeteria overlooking the Pacific Ocean together with our jolly group of physicists. It was at one of these lunches that Joe told me, with a faint but very satisfied smile: "I showed that Dirichlet branes in superstring theory carry Ramond-Ramond charges." These few words changed the course of string theory and had ramifications in fields far beyond.

Although his life was too short, it was a life well-lived. Joe describes an undergraduate summer working for Tom Tombrello at Caltech as "This was heaven: four of us sharing a basement office in Bridge . . . talking physics all day," a joy he carried with him his whole life. Few among us can confidently state, "I have had an impact on the most fundamental questions of science." His summary of his seizure in Berlin and subsequent diagnosis of terminal brain cancer with "Well, that sucks" are the words of a man with few regrets.

Joe was a family man. He loved and was loved by his wife Dorothy and sons Steven and Daniel, as well as his many friends. The last time I saw him at his house was for a game of pickleball with his family at their newly installed backyard court. Joe loved sports as much as physics and, ignoring his cancer, he was taking pickleball on, methodically, cheerfully and wholeheartedly, as a new challenge to be overcome. He lived life to its fullest right to the very end.

We miss him.

Andrew Strominger

EDITOR'S NOTE

I'm addicted to Joe. That was the title of a short presentation I gave during a Kavli Institute of Theoretical Physics (KITP) conference in 2014 celebrating Joe's sixtieth birthday. I described the process whereby a student gradually morphs into their advisor as they pick up more and more of their advisor's quirky habits. With Joe, that included his continuous torrent of "uh-huh" as he followed an explanation, his quick "yes, yes, YES" in increasing volume and intensity in anticipation of the conclusion, his slow "well, well" if he didn't completely buy it, and his occasional frantic-head-scratch-with-broad-grin combo when trying to focus.

Also during that talk, I disclosed the real reason for asking Joe to be my PhD advisor. Oddly enough, I didn't know who Joe was when I first started as a graduate student at the University of California at Santa Barbara (UCSB). I mean, I knew that he was the inventor of D-branes, but UCSB had a stellar team of high energy physicists, all of whom are known for something, and I was a bit too young and inexperienced to appreciate their differences. Picking an advisor is one of the most important decisions a graduate student has to make, with career-defining consequences, but it's also one that has to be made fast before all the available options fill up. I remained indecisive, and anxious, for about a year.

All that changed when I got a "sign" at the local mosque in Santa Barbara. No, this isn't the story of a supernatural religious experience or of finding Joe's name in scripture, but of a serendipitous encounter with a visiting physicist. I stuck around as I usually do following the prayer service, waiting to make casual conversation, when I saw a friend eagerly walk toward me while beckoning someone to follow. He introduced me to M. Zahid Hasan, the visiting physicist, and let us be. After a round of personal and professional introductions, I thought I'd seek Zahid's input on what was plaguing my mind. I figured that he probably didn't know the high energy physics faculty well enough to answer my question directly, so I decided on general advice instead. I wanted him to avoid being generic, so I phrased my request to stimulate some introspection. I asked: "I want you to give me that one piece of advice that you wish somebody had given you." As I was finishing my request, I took notice of a subtle change in his posture, something typical of physicists as they engage with a problem, and I knew right then and there that this was going to be good. I was all ears.

It happened in a split second. He looked down momentarily searching for the answer, found it, then raised his head and said: "Work with Joe." Now *that* I did not see coming! It was as good a sign as any, and so I scheduled a meeting with Joe and *declared* to him that he would be my advisor, and that I would not take no for an answer. I was fortunate that he agreed.

Coming back to the present, I am also grateful to be the editor of Joe's memoir that you hold before you. The main text of this memoir is a light editing of the one that's already up on the web. I made sure to run these edits by Dorothy Chun, Joe's wife, and his longtime friend and colleague Stephen Shenker, both of whom you'll read about extensively in the memoir. I wanted to ensure that the text retained Joe's signature voice. This version of the memoir also contains a selection of photographs curated mostly by Dorothy and her two sons, Steven and Daniel. The cover of the memoir features a diagram representing Joe's "favorite type" of physics calculation: a vacuum amplitude of an open string anchored between two of Joe's D-branes.

A further addition to the memoir is a collection of physics explanation boxes meant to complement Joe's own description of the physics. They provide further background and intuition on the topics that Joe has either worked on or has deemed important. I agonized a lot over the level of the explanations and settled on that of an advanced undergraduate and beginning graduate student in physics. My reasoning was that, among all audiences who might be interested in reading this book, this category is the one that stands to benefit the most. Nevertheless, I hope that everyone will get something out of them.

This version of the memoir also features a set of bibliographic notes that include references to the works appearing in the main text, along with other useful related material. It is intended to be a resource for those wanting to delve deeper into the physics.

In addition to help from Joe's family and Stephen Shenker, I am indebted to suggestions from Edward Witten, Makoto Natsuume (Joe's ninth student), Ben Michel (Joe's third-to-last student), and Joe's other students, friends, and colleagues.

In closing, I just wanted to say how lucky I am for having Joseph Polchinski as my PhD advisor, mentor, role model, and dear friend. I deeply miss him. He's left a permanent mark on my personality and physics that I will forever cherish. Truly, to this day, my gauge for whether a physics problem is worth pursuing is whether I think Joe would do so. I wasn't kidding about my addiction. In fact, "I'm (Still) Addicted to Joe" was the title of another talk I gave at KITP in late 2018 at a symposium celebrating Joe's life.

To those reading these words and about to embark on a journey with Joe, consider yourselves warned: you too run the risk of getting hooked . . .

Ahmed Almheiri

1 EARLY YEARS

1.1 FAMILY HISTORY

Whenever I am asked where I am from, I always want to answer "Caltech." In fact, I did not set foot on the Caltech campus, and barely in the state of California at all, before graduating from high school in Tucson, Arizona. But Caltech was so formative in my life that anything that came before pales in comparison for me. However, I will start in the usual way, with a bit of family history. This gives some context for later life, and may provide unexpected insights.

In the town of Hawthorne, in Westchester County, New York, you can find the Joseph Polchinski Company,[1] which has sold cemetery monuments since 1883. It was founded by my great-grandfather, whose name I share.[2] My father shared the same name, but my grandfather was an *Arthur*. So I am a *Junior*. Among family I was distinguished as *Joey*, and a few of them continue to use this even now.

My father's grandparents came to the United States around 1870, part of the vast European migration driven by the combination of starvation and ambition. One of them, Joseph, was from the region between Poland and Germany, while the other three were from Ireland. Joseph brought his expertise in stonework with him, founding the monument company and the florist next door. These supported his family for two generations, before they began to spread in the usual American way. The monument company is now owned by another family, but I am always honored to see that they have kept the name for its historic value.

I know much less about the family of my mother, Joan Thornton. From a very young age she was raised in a series of foster homes. She ended up with a warm-hearted German-American family, but she seemed to retain a melancholy from her difficult earlier years. I got only some basic history about her, and she never felt a desire to learn more. She was born in Pennsylvania, but her final foster family was in the same New York town as Joseph Polchinski's family and his monument company. Her ancestry was a mixture of Irish and other parts of the British Isles.

Growing up in the same small town, my parents Joan Thornton and Joe Polchinski married in 1951, when Joan was nineteen and Joe was twenty-two. I was born three years later, in 1954, and my sister Cindy three years after. Our family was a rather typical one for the rising American middle class in the 1950s. My father left the family business to earn a degree in accounting. He went to work for Schenley, a distiller, commuting by train to his job at

Figure 1.1
Polchinski family, New York, ca. 1960

the Empire State building. My mother worked for a few years in an office, then became a full-time homemaker.

Neither of my parents expressed an interest in science. My father did say that he had wanted to study chemistry but could not because he had not taken German. But our conversations rarely turned to science. More common subjects were sports and games, though we did like games like bridge which had some aspect of mathematics. He was highly competitive, a trait that I picked up. In other directions, my father's reading tended toward history, and my mother's toward fiction.

1.2 EARLY SCIENCE AND MATH

My own interest in science appeared early. When I was six, my passion was the *How and Why Wonder Books of Science*. This was a series of several dozen books, each centering on a subject such as Dinosaurs, Atomic Energy, Chemistry, and Rocks and Minerals. Each was forty-eight pages long, but in a large format that was packed with information. The figures were hand-drawn but appealing. I waited eagerly for each new issue. Once, I misbehaved rather badly, playing with an ember from a campfire, and the new issue was taken away from me for a few days; it was an effective punishment.

A few years later, Isaac Asimov's books in math and science drove me. So also did science fiction, by Asimov, Clarke, and many others, giving an inspiring if unrealistic picture of what science might do. Unfortunately, the science books and teachers through high school made little impression. At that level the subject was too purely descriptive.

I remember asking my physics teacher, what is the speed of gravity? He did not understand the question, even though I drew a diagram illustrating how you would measure it. Another misunderstanding, at an earlier age, was a test question: Which is strongest: (a) pressure, (b) electricity, (c) gravity, or (d) magnetism? I knew that the question made no sense, but having good test-taking instincts I knew they wanted the answer *Gravity*. But this could not be correct: I could lift up my hand even against the gravitational attraction of the entire earth. So I chose another answer almost randomly, refusing to make the choice that I knew was wrong. I probably made a token argument with the teacher, but I was used to losing those. But the smallness of gravity is indeed one of the principles of physics.[3]

One very exciting moment, on the other hand, was reading (no equations at this level) how an electric field can make a magnetic field, and a magnetic field can make an electric field, and these two together made a wave that was the origin of light. So my future in science was clear, even if it took a few more years to get the details. Thus, from an early age I was drawn to the basic principles of physics. I am very fortunate that I have been able to spend my life studying this, and contributing new understandings.

With math, one gets closer to the real subject at a younger age, so the classes were more interesting. I raced through my courses, meeting the new math in fifth grade. This program was a response to *Sputnik*, and the perception that the US was falling behind the Soviets in science (the *How and Why* books likely had the same origin). I can remember the school assembly, where all the students and their parents learned about this new thing. The plan was actually rather bizarre. Students would first learn such abstract notions as sets and operations, only moving on to arithmetic after the theory was understood. It is hard to believe that anyone thought this was a good idea, and indeed it faltered in a few years, but it was perfect for me.[4]

Unfortunately, I missed the full benefit of the new math because we moved to Tucson, Arizona, a year later. My father was looking for a better job, as an account manager at Merrill Lynch, a stock brokerage, and Tucson had one of the available openings. Perhaps too my parents were ready to leave the small town they had grown up in. So the chance to race ahead in math was delayed a little. I missed another chance around the same time: my father was second in line among the applicants for a position as business officer at the Institute for Advanced Study, where my connection with science may have been accelerated.

Canyon del Oro (CDO), my combined junior high/high school, was a new school, and a small one, which would limit me in some ways. But I had the good fortune that my first math class was with Ed Baceski. Mr. Baceski loved math, and he made it a game. For example, completing a problem set would lead to a code to unravel (and you could short-circuit the problem set by working backward). In retrospect, Baceski was a bit like the new math, not ideal for the typical student, but great for me and a few others. Early on he set the Gauss problem, summing 1 to 100, and after I solved a few of these I was allowed to race on in the textbook on my own. I completed four years in one, through geometry. My most vivid memory was starting trigonometry, reading on my own, and not getting the point of this *sine* and *cosine*. But after a couple of days it suddenly fell into place, and it was wonderful.

The next year, I took advanced algebra, the highest level offered in this small school. It was taught by the football coach, leading to more of the sorts of disagreements that a student doesn't win. In retrospect, there might have been a right way and a wrong way to make such points.

Having run out of math classes, I spent my first high school year commuting evenings to the University of Arizona for calculus, driving with my father or some older students. Unfortunately, this did not go well. Part of this was the instructor, who contributed little insight or inspiration. One day we had a substitute, who regaled us with stories about math, and in particular challenged my precocity with examples of great mathematicians who had accomplished much more much earlier than I (he could see that I was full of myself and needed this). But then it was back to the regular teacher.

The second problem was that I couldn't really grasp calculus, just as earlier I couldn't get trigonometry for a while. But in this case it took three years, when I took college physics and found out what calculus was really for. (Mathematicians might tell you that it has other uses, but they would be wrong.)

Disappointed by the class, I decided I could learn math on my own. I chose a book on group theory. Unfortunately, I again seemed to lack the knack of the subject, and my effort faded. I ended up spending most of my last two years of high school studying no math. Science was similar. My small school had no advanced courses, so after racing through the sciences that were available I found myself with a year of no math or science classes at all, spending it taking the other required courses to graduate a year early.

1.3 FAMILY

My sister Cindy and I seem as different as two people can be, in personality, interest, and career. Where my passion was physics, hers was animals, horses in particular. She took only one year of college, and that was to mollify our dad. She was then a groom at a large stable near Santa Barbara. Over the years she has owned horses, bred them, competed with them, and most recently served as steward at horse shows all over the country.

To support her interests, she also served as a police officer for almost twenty years. This is something I could not imagine doing; for one thing, I can't make quick decisions. But she did this with aplomb. Cindy is not academic in her interests, but she is extremely capable. Yet another difference is that I have always been shy, working up from extreme shyness when young to mere introversion today. My sister is the opposite, taking great pleasure in meeting and talking with people from many walks of life.

In spite of our differences, we have always gotten along well, and she is a great supporter. She has often told me that she looks forward to traveling with me to Sweden when I win the Nobel. That is not going to happen, but I did take her to the Large Hadron Collider (LHC) a few years ago.

My parents were as helpful as they could be, given that they did not understand what this alien in their family was doing. My father was the type who always had to be in charge. When I told him what I was learning in school, especially later on when we got to relativity, he told me that this could not be true. So my father, I am sorry to say, was a bit of a crackpot when it came to physics. The number of people who have never studied science but still feel qualified to present their ideas is remarkably large: notably, 99 percent of them are male. Indeed, my mother did not have such theories. She did make it a point, many years later, to tell me that she had been very smart in school. Unfortunately, the limitations experienced by so many women prevented her from pursuing this.

1.4 INTERESTS

I did have some stimulation outside of school, notably science fiction, telescopes, and chess. I mentioned science fiction before. It is curious to recall that this was almost entirely through books. *Star Wars* was still seven years away, and with a few exceptions like *War of the Worlds* and *2001: A Space Odyssey*, there was not a big market for science fiction movies. It is remarkable how it now dominates.

My interest in telescopes began with the surprise gift of a four-inch reflector from my parents when I was twelve. This was an excellent idea. Tucson was then a rather small city, and we lived on the edge, where well-separated houses trailed off into desert. The seeing (air clarity) and darkness were incredible. My interest was drawn to picking out galaxies, finding as many of the Messier catalog as I could. My interest was mostly visual; I was too young to follow the science.

After exhausting the potential of the four-inch, I set out to build an eight-inch reflector. I did not have a large budget or a lot of mechanical aptitude, so the results were mixed. I made a creditable mirror, working it against another glass using progressively finer grit and measuring my progress with the help of the University of Arizona's astronomy club. But the mechanical support was built with whatever wood I could get hold of, patterned on a scaled picture of the Hale telescope. This worked, and was great for showing off, but it was well short of the real capacity of an

Figure 1.2
Joe and the telescope he built, Tucson, ca. 1966

eight-inch. Still, finding the Crab Nebula was one of my favorite challenges. Seeing Andromeda was easy even by eye, and I still can pick it out in Santa Barbara on a good day.

Chess dominated much of my school years. I learned the moves from my father when I was young (aside from some confusion about the pawns). After occasional games with my father and a few friends, my interest exploded when I got to CDO and discovered a group to play with. For the next five years, at almost every lunch period or other break, we would pull out our boards and play. As I got better, I played in local tournaments, and in larger ones in Phoenix. This was a lot of fun, and virtually my only social life. In my last two years, when I had run out of math and science to study in class, I spent many hours studying chess books, about chess openings, and attacks, in particular.

There is an anomaly here, which has always puzzled me. Based on my progress in physics, first in progressively more advanced courses, then in original research, and finally in significant discovery, you could say that in physics I am the analog of a fairly strong Grandmaster. In chess, I started out as a beginner, and in a few years had worked my way up to the level of a good recreational player. In my last two years, working nearly full-time on chess, I expected to continue to improve. Instead, I came to a virtual standstill.

Chess has a nice numerical system, called Elo. Based on their wins and losses, each player has a numerical rating. Grouping them, they are designated . . . < *D* < *C* < *B* < *A* < *Expert* < *Master* < *Senior Master* < *Grandmaster*. Roughly speaking (the full theory is more elaborate), if two players are separated by M levels, the relative probability that the higher ranked player wins is 3^M. When I started out I was a *D*, a beginner, and after three years I rose to *A*. But I never quite reached *Expert*, much less the promised land of *Master* and beyond.

I have always wondered why. Are chess and physics so different, that one can be a Grandmaster in one, and not even an Expert in the other, in spite of similar efforts? Seeing younger and younger teens achieve Grandmaster has always amazed me.

I got one clue when I ran into a high school chess buddy many years later. When I had first met Keith Nelson in school, he challenged me to a game. Having faced such challenges often, I expected a quick victory, but he beat me. I was sure that with a bit more concentration, I would set things right. But he beat me again! Over time I won a share of the games, but he was clearly the better player. So, perhaps twenty years later, I ran into Keith again. I had not known of his interest in science, but he had in fact become a professor of experimental chemistry at MIT. And as we began to reminisce, he astonished me by recounting in detail our first two games, which I could remember only dimly. Evidently, he had a phenomenal memory, at least compared with mine.

Indeed, I have always felt that I did not have an especially good memory. In one of my first classes in college, the instructor told us that you do not need a good memory to do physics, because you can derive everything from first principles. If I had had any doubts that this was the right field for me, that sealed it!

Beyond the issue of memory, I did not have a real knack for chess. I was conservative, using a few basic attacks and waiting for the opponent to make a mistake. I did not like to advance pawns, because the effect is irreversible. This is not the way that Grandmasters think! Likely with training I could have done much better, but not been a prodigy. I am curious, what distinguishes these different mental strengths?

1.5 TRAITS

One thing I want to do is to recall some of my development as a physicist. There are a number of traits that have played a role here. Many of these have already come up in the discussion of my early life.

To start with, my parents and relatives could see from a very early age that I was not a normal kid. I could solve puzzles and games at a level far above my age, and my general knowledge was advanced. So from a young age, this was my identity: being very smart. It has stayed with me as I have moved from level to level, all the way to string theory.

On the other hand, I have noted that I was painfully shy all through school. I tried to keep conversations as short as possible, so as not to bore people. Only gradually, in college and beyond, did this fade.

I also think I have some lack of common sense. My poor telescope design was one example. Another was my two-year gap in high school math: with common sense I should have looked for advice. And my approach to chess also seems to show a lack of common sense.

In a sense, shyness and lack of common sense were two sides of the same coin. If you talk to other people you learn things. If you don't, you have to figure everything out yourself. Even after maturing from shyness to introversion, I tend not to ask questions or seek help. This may be one of the reasons that my science didn't really reach its peak until rather late.

Notes

1. [The Joseph Polchinski Company has since been renamed Polchinski Memorials, Inc.—Ed.]

2. [A picture of Joe's great-grandfather appears on the memorial website: https://www.polchinskimemorials.com/about-us-3/.—Ed.]

3. In retrospect, gravity could have been correct, depending on the context. Since gravity is the only force that is always additive, a large enough body of matter will attract with great strength. So in the extreme case, gravity does win.

4. I have just learned, from Wikipedia, that Richard Feynman was on the California State Curriculum Commission at just this time and was one of those to criticize the new math.

BIBLIOGRAPHIC NOTES

This section provides references to works described by Joe in the main text of the memoir. It is by no means an exhaustive list for each of the topics discussed. Review articles and/or books will be included for some general topics mentioned without reference in the main text.

CHAPTER 2

2.2

Bill Zajc got his head start by reading Richard P. Feynman, Robert B. Leighton, and Matthew L. Sands, *The Feynman Lectures on Physics* (Reading, MA: Addison-Wesley, 1963).

2.8

Joe mentions that he learned QFT using the old text by James D. Bjorken and Sidney David Drell, *Relativistic Quantum Mechanics* (New York: McGraw-Hill, 1964). I'd personally recommend some of the newer standard texts such as Mark Srednicki, *Quantum Field Theory* (Cambridge: Cambridge University Press, 2007), for its clarity and explicitness, and Michael E. Peskin and Dan V.

Schroeder, *An Introduction to Quantum Field Theory* (Boulder, CO: Westview Press, 1995), for its high focus on physical reasoning.

The Big Black Book of GR is Charles W. Misner, Kip S. Thorne, and John Archibald Wheeler, *Gravitation* (San Francisco, CA: W. H. Freeman, 1973). The more standard way of learning GR nowadays is through Robert M. Wald, *General Relativity* (Chicago: University of Chicago Press, 1984), or the more accessible Sean M. Carroll, *Spacetime and Geometry: An Introduction to General Relativity* (Cambridge: Cambridge University Press, 2019).

CHAPTER 3

3.3

Diagnosing confinement via the Wilson loop was proposed in Kenneth Wilson, "Confinement of Quarks," *Physical Review D* 10 (1974). The electromagnetic dual of this operator, the 't Hooft vortex operator, was discussed in Gerard 't Hooft, "On the Phase Transition towards Permanent Quark Confinement," *Nuclear Physics B* 138 (1978). Joe's construction of the 't Hooft operator can be found in his dissertation: Joseph Polchinski, "Vortex Operators in Gauge Field Theories" (PhD diss., University of California, Berkeley, 1980). As Joe says, this problem was not completely solved until the work of Kapustin, found in Anton Kapustin, "Wilson-'t Hooft Operators in Four-Dimensional Gauge Theories and S-Duality," *Physical Review D* 74 (2006).

3.6

More books on QFT include K. Nishijima, *Fields and Particles: Field Theory and Dispersion Relations*, 4th ed. (San Francisco, CA: Benjamin Cummings, 1998); Raymond F. Streater and Arthur S.

Wightman, *PCT, Spin and Statistics, and All That* (Princeton, NJ: Princeton University Press, 2000); and N. N. Bogoliubov and D. V. Shirkov, *Introduction to the Theory of Quantized Fields* (Geneva: Interscience Publishers, 1959), the last of which used to be the standard text for learning about renormalization.

The advances in QFT in the 1970s include the discovery of monopoles in QFT found in Gerard 't Hooft, "Magnetic Monopoles in Unified Gauge Theories," *Nuclear Physics B* 79 (1974), and Alexander M. Polyakov, "Particle Spectrum in the Quantum Field Theory," *Journal of Experimental and Theoretical Physics Letters* 20 (1974), and the discovery of instantons in Alexander A. Belavin et al., "Pseudoparticle Solutions of the Yang-Mills Equations," *Physics Letters B* 59 (1975). The rediscovery of bosonization was shown in Sidney Coleman, "Quantum Sine-Gordon Equation as the Massive Thirring Model," *Physical Review D* 11 (1975).

Coleman's lectures, compiled in his book *Aspects of Symmetry: Selected Erice Lectures* (Cambridge: Cambridge University Press, 1988), is a highly recommended resource for any serious student of QFT.

CHAPTER 4

4.1

Coleman's theorem forbidding spontaneous breaking of continuous symmetry in 1 + 1-dimensional QFT, due to its propagators being IR divergent, is proven in Sidney Coleman, "There Are No Goldstone Bosons in Two Dimensions," *Communications in Mathematical Physics* 31 (1973).

The classification of electric and magnetic fluxes by 't Hooft that Joe was interested is in is Gerard 't Hooft, "A Property of Electric and Magnetic Flux in Nonabelian Gauge Theories," *Nuclear Physics B* 153 (1979). The lattice model which seemed to contradict its results was discussed in Gerhard Mack and Valentina B. Petkova, "Comparison of Lattice Gauge Theories with Gauge Groups Z(2) and SU(2)," *Annals of Physics* 123 (1979), and Laurence G. Yaffe, "Confinement in SU(N) Lattice Gauge Theories," *Physical Review D* 21 (1980). Joe's work showing how these models are in fact consistent with 't Hooft's conditions when all the fluxes are correctly accounted for is Joseph Polchinski, "Order Parameters in a Modified Lattice Gauge Theory," *Physical Review D* 25 (1982).

On the comparison between the short, slick physics argument versus the long, rigorous proof, Joe brings up Alexander M. Polyakov, "Quark Confinement and Topology of Gauge Theories," *Nuclear Physics B* 120 (1977) versus Markus Göpfert and Gerhard Mack, "Proof of Confinement of Static Quarks in 3-Dimensional U(1) Lattice Gauge Theory for All Values of the Coupling Constant," *Communication in Mathematical Physics* 82 (1982), respectively. The general argument for the difficulty of proving confinement is given in Gerard 't Hooft, "On the Phase Transition towards Permanent Quark Confinement," *Nuclear Physics B* 138 (1978).

4.3

A description of the standard model and its possible extensions, including supersymmetry, can be found in the more modern QFT texts given above.

Unifying the forces of the standard model into a single grand unified theory was proposed in Howard Georgi and S. L. Glashow, "Unity of All Elementary-Particle Forces," *Physical Review Letters* 32 (1974).

4.4

Witten's work on cancellation of *D*-term corrections is in Edward Witten, "Mass Hierarchies in Supersymmetric Theories," *Physics Letters B* 105 (1981). Joe's collaborative work demonstrating the cancellation of quantum corrections and the charge sum rule is Willy Fischler, Hans-Peter Nilles, Joseph Polchinski, Stuart Raby, and Leonard Susskind, "Vanishing Renormalization of the D-Term in Supersymmetric U(1) Theories," *Physical Review Letters* 47, (1981).

4.5

An example construction of realistic SUSY models of physics is Luis Álvarez-Gaumé, Mark Claudson, and Mark Wise, "Low-Energy Supersymmetry," *Nuclear Physics B* 207 (1982).

The stability of the various energy scales under SUSY breaking was studied in Joseph Polchinski and Leonard Susskind, "Breaking of Supersymmetry at Intermediate Energy," *Physical Review D* 26 (1982). Further analysis of this question was pursued by Joe in Joseph Polchinski, "Gauge-Fermion Masses in Supersymmetric Hierarchy Models," *Physical Review D* 26 (1982), and Joseph Polchinski, "Effective Potentials for Supersymmetric Three-Scale Hierarchies," *Physical Review D* 27 (1983).

Susskind's work on the connection between information loss and energy nonconservation is Thomas Banks, Leonard Susskind, and Michael Peskin, "Difficulties for the Evolution of Pure States into Mixed States," *Nuclear Physics B* 244 (1984).

4.6

The project Joe worked on during his stop at Aspen is Mary K. Gaillard, Lawrence J. Hall, Bruno Zumino, Francisco del Aguila, Joseph Polchinski, and Graham G. Ross, "Light Scalars in N = 1 Locally Supersymmetric Theories," *Physics Letters B* 122 (1983).

CHAPTER 5

5.1

Joe's "initiation" project at Harvard was published in Joseph Polchinski and Mark B. Wise, "On the Generality of the Mass Sum Rule," *Nuclear Physics B* 218 (1983).

5.2

While avoiding SUSY, Coleman was busying himself with magnetic monopoles in Sidney Coleman, "The Magnetic Monopole Fifty Years Later," in *Proceedings, Les Houches Summer School in Theoretical Physics: Gauge Theories in High Energy Physics*, ed. Mary K. Gaillard and Raymond Stora (Les Houches, 1981), 461–552; with 't Hooft anomaly cancellation in Sidney Coleman and Bernard Grossman, "'t Hooft's Consistency Condition as a Consequence of Analyticity and Unitarity," *Nuclear Physics B* 203 (1982); and with topological solitons in Sidney Coleman, "Q-Balls," *Nuclear Physics B* 262 (1985).

5.4

Joe's work on finding a realistic model of supergravity is in Luis Álvarez-Gaumé, Joseph Polchinski, and Mark B. Wise, "Minimal Low-Energy Supergravity," *Nuclear Physics B* 221 (1983). As is footnoted in the main text, some results had already been discovered in Luis Ibáñez and Graham G. Ross, "$SU(2)_L \times U(1)$ Symmetry Breaking as a Radiative Effect of Supersymmetry Breaking in GUTs," *Physics Letters B* 110 (1982). The follow-up work is Benjamin Grinstein, Joseph Polchinski, and Mark B. Wise, "W and Z Decays in Low Energy Supersymmetry," *Physics Letters B* 130 (1983).

5.5

Joe's seminal work on renormalization is Joseph Polchinski, "Renormalization and Effective Lagrangians," *Nuclear Physics B* 231 (1984).

Balaban's proof of asymptotic freedom culminates in Tadeusz Balaban, "Large Field Renormalization. 2: Localization, Exponentiation, and Bounds for the R Operation," *Communications in Mathematical Physics* 122 (1989). The entire series is included in this paper's bibliography.

5.6

The presence of magnetic monopoles in GUTs was first shown in Gerard 't Hooft, "Magnetic Monopoles in Unified Gauge Theories," *Nuclear Physics B* 79 (1974), and Alexander M. Polyakov, "Particle Spectrum in the Quantum Field Theory," *Journal of Experimental and Theoretical Physics Letters* 20 (1974).

Baryonic size controlling of the rate of baryon number violating processes was shown in Valery A. Rubakov, "Adler-Bell-Jackiw Anomaly and Fermion-Number Breaking in the Presence of a Magnetic Monopole," *Nuclear Physics B* 203 (1982), and Curtis G. Callan, Jr., "Dyon-Fermion Dynamics," *Physical Review D* 26 (1982). Joe's toy model for this is in Joseph Polchinski, "Monopole Catalysis: The Fermion-Rotor System," *Nuclear Physics B* 242 (1984).

The other Rubakov work on baryon number violation at high temperatures is in Vadim A. Kuzmin, Valery A. Rubakov, and Mikhail E. Shaposhnikov, "On the Anomalous Electroweak Baryon Number Nonconservation in the Early Universe," *Physics Letters B* 155 (1985). The work involving Joe trying to understand this is Michael Dine, Olaf Lechtenfeld, Bunji Sakita, Willy Fischler, and Joseph Polchinski, "Baryon Number Violation at High Temperature in the Standard Model," *Nuclear Physics B* 342 (1990).

Rubakov and Shaposhnikov investigated the braneworld idea in Valery A. Rubakov and Mikhail E. Shaposhnikov, "Do We Live Inside a Domain Wall?," *Physics Letters B* 125 (1983).

5.7

The work Joe reported on was his work with Álvarez-Gaumé and Wise (referenced in section 5.4 above).

The attempt to explain monojets using supersymmetry was in Lawrence J. Hall and Joseph Polchinski, "Implications of Supersymmetric Origins for Monojets," *Physics Letters B* 152 (1985).

Explaining the putative new signal using wave-function effects was done in Joseph Polchinski, Stephen R. Sharpe, and Ted Barnes, "Bound State Effects in $\Upsilon \rightarrow \zeta(8.3) + \gamma$," *Physics Letters B* 148 (1984), and James Pantaleone, Michael E. Peskin, and S.-H. Henry Tye, "Bound-State Effects in $\Upsilon \rightarrow \gamma +$ Resonance," *Physics Letters B* 149 (1984).

CHAPTER 6

6.3

It goes without saying that *the* authoritative text on string theory is Joe's very own *String Theory*, which was published in the two volumes: Joseph Polchinski, *String Theory: An Introduction to the Bosonic String*, vol. 1 (Cambridge: Cambridge University Press, 1998), and Joseph Polchinski, *String Theory: Superstring Theory and Beyond*, vol. 2 (Cambridge: Cambridge University Press, 1998). A useful supporting document to this is Joe's string theory course notes titled *Joe's Little Book of String*, found online at https://www.kitp.ucsb.edu/sites/default/files/users/joep/JLBS.pdf.

The cancellation of anomalies in superstring theories with chiral fermions is found in Michael B. Green and John H. Schwarz, "Anomaly Cancellations in Supersymmetric D = 10 Gauge Theory and Superstring Theory," *Physics Letters B* 149 (1984).

Heterotic string theory, which could accommodate something like the standard model, was discovered in David J. Gross, Jeffrey A. Harvey, Emil Martinec, and Ryan Rohm, "Heterotic String," *Physical Review Letters* 54(1985).

Solutions of compactified string theory on Calabi-Yau spaces was first found in Philip Candelas, Gary T. Horowitz, Andrew Strominger, and Edward Witten, "Vacuum Configurations for Superstrings," *Nuclear Physics B* 258 (1985).

Work on effective strings in any dimension, not those required by actual strings, was done in Joseph Polchinski and Andrew Strominger, "Effective String Theory," *Physical Review Letters* 67 (1991).

Joe's papers on the Polyakov path integral include Joseph Polchinski, "Evaluation of the One Loop String Path Integral," *Communications in Mathematical Physics* 104 (1986); Joseph Polchinski, "Vertex Operators in the Polyakov Path Integral," *Nuclear Physics B* 289 (1987); and Joseph Polchinski, "Factorization of Bosonic String Amplitudes," *Nuclear Physics B* 307 (1988).

Joe's collaborations on aspects of the Polyakov path integral regarding off-shell amplitudes and supersymmetry are Andrew

Cohen, Gregory Moore, Philip Nelson, and Joseph Polchinski, "Semi-Off-Shell String Amplitudes," *Nuclear Physics B* 281 (1987), and Gregory Moore, Philip Nelson, and Joseph Polchinski, "Strings and Supermoduli," *Physics Letters B* 169 (1986). Erratum: *Physics Letters B* 201 (1988).

6.4

The breaking of $N=2$ down to $N=1$ by vortices was shown in David Lancaster, "Instanton Contributions to Supersymmetric Ward Identities," *Nuclear Physics B* 238 (1984). Joe's work with Hughes on working out the four-dimensional action of $N=2$ to $N=1$ breaking is in James Hughes and Joseph Polchinski, "Partially Broken Global Supersymmetry and the Superstring," *Nuclear Physics B* 278 (1986), and James Hughes, Jun Liu, and Joseph Polchinski, "Supermembranes," *Physics Letters B* 180 (1986). The extension to the case of $D=6$ to $D=4$ is in James Hughes, Jun Liu, and Joseph Polchinski, "Virasoro-Shapiro from Wilson," *Nuclear Physics B* 316 (1989).

The supposed no-go theorem precluding the breaking of SUSY from $N=2$ to $N=1$ in four dimensions uses the argument in Rudolf Haag, Martin Sohnius, and Jan T. Łopuszański, "All Possible Generators of Supersymmetries of the S-Matrix," *Nuclear Physics B* 88 (1975).

Classification of all possible membranes was performed in the seminal works Eric Bergshoeff, Ergin Sezgin, and Paul K. Townsend, "Superstring Actions in D = 3,4,6,10 Curved Superspace," *Physics Letters B* 169 (1986), and Eric Bergshoeff, Ergin Sezgin, and Paul K. Townsend, "Supermembranes and Eleven-Dimensional Supergravity," *Physics Letters B* 189 (1987).

Understanding the potential anomaly in superstring theory and its cancellation from the perspective of the fundamental string was done in Joseph Polchinski and Yunhai Cai, "Consistency of Open Superstring Theories," *Nuclear Physics B* 296 (1988).

6.5

The monotonicity of the scale transformation was shown in Alexander B. Zamolodchikov, "'Irreversibility' of the Flux of the Renormalization Group in a 2D Field Theory," *JETP Letters* 43 (1986), which Joe used to prove that scaling symmetry implies conformal symmetry in Joseph Polchinski, "Scale and Conformal Invariance in Quantum Field Theory," *Nuclear Physics B* 303 (1988).

Witten analyzed the production of cosmic strings in superstring theory in Edward Witten, "Cosmic Superstrings," *Physics Letters B* 153 (1985).

On the question of strings passing through each other, the numerical analysis on GUTs strings was done in Richard A. Matzner, "Interaction of U(1) Cosmic Strings: Numerical Intercommutation," *Computers in Physics* 2 (1988), while the analytic study for the fundamental string was done by Joe in Joseph Polchinski, "Collision of Macroscopic Fundamental Strings," *Physics Letters B* 209 (1988). The follow-up with open strings is Jin Dai and Joseph Polchinski, "The Decay of Macroscopic Fundamental Strings," *Physics Letters B* 220 (1989).

The work on mirror symmetry is Philip Candelas, Xenia C. De La Ossa, Paul S. Green, and Linda Parkes, "A Pair of Calabi-Yau Manifolds as an Exactly Soluble Superconformal Theory," *Nuclear Physics B* 359 (1991).

Weinberg's work on string theory vertex operators is Steven Weinberg, "Coupling Constants and Vertex Functions in String Theories," *Physics Letters B* 156 (1985), and on the finiteness of the bosonic open string is Steven Weinberg, "Cancellation of One-Loop Divergences in SO(8192) String Theory," *Physics Letters B* 187 (1987).

Cancellations in the dilaton energy between string amplitudes and loop divergences were studied in Willy Fischler and Leonard Susskind, "Dilaton Tadpoles, String Condensates and Scale Invariance," *Physics Letters B* 171 (1986), and Willy Fischler and Leonard Susskind, "Dilaton Tadpoles, String Condensates and Scale Invariance II" *Physics Letters B* 173 (1986).

The work by the "international students" on the low energy effective action of the string is Clifford P. Burgess, Anamaría Font, and Fernando Quevedo, "Low-Energy Effective Action for the Superstring," *Nuclear Physics B* 272 (1986).

CHAPTER 7

7.1

The book on string theory utilizing mostly the light-cone methods is Michael B. Green, John H. Schwarz, and Edward Witten, *Superstring Theory*, vols. 1 and 2 (Cambridge: Cambridge University Press, 1987).

The work on heavy quark theory that Joe "regretted" missing out on was Nathan Isgur and Mark B. Wise, "Weak Decays of Heavy Mesons in the Static Quark Approximation," *Physical Letters B* 232 (1989).

7.2

Joe's seminal work with his students introducing D-branes and connecting different string theories via *T*-duality is Jin Dai, Robert G. Leigh, and Joseph Polchinski, "New Connections between String Theories," *Modern Physics Letters A* 4 (1989). Earlier work showing that the two type II theories were T-dual is Michael Dine, Patrick Y. Huet, and Nathan Seiberg, "Large and Small Radius in String Theory," *Nuclear Physics B* 322 (1989).

The works Joe refers to by Hořava and Green in a footnote are Petr Hořava, "Background Duality of Open String Models," *Physics Letters B* 231 (1989), and Michael B. Green, "Modifying the Bosonic String Vacuum," *Physics Letters B* 201 (1988).

p-Branes were introduced in Ana Achucarro, Jonathan M. Evans, Paul K. Townsend, and David L. Wiltshire, "Super p-Branes," *Physical Letters B* 198 (1987).

The original argument precluding the standard model from type IIA, B was presented in Lance J. Dixon, Vadim Kaplunovsky, and Cumrun Vafa, "On Four-Dimensional Gauge Theories from Type II Superstrings," *Nuclear Physics B* 294 (1987).

The effective field theory for the D-branes was worked out in Robert G. Leigh, "Dirac-Born-Infeld Action from Dirichlet Sigma Model," *Modern Physics Letters A* (1989).

Showing that the two heterotic theories are T-dual was done in Kumar S. Narain, "New Heterotic String Theories in Uncompactified Dimensions < 10," *Physical Letters B* 169 (1986).

7.3

The ability to formulate string theory in dimensions other than 10 and nonzero vacuum energy was shown in Robert C. Myers, "New Dimensions for Old Strings," *Physical Letters B* 199 (1987). Joe's work on trying to construct examples with small CC is in Shanta P. de Alwis, Joseph Polchinski, and Rolf Schimmrigk, "Heterotic Strings with Tree Level Cosmological Constant," *Physical Letters B* 218 (1989).

The physics of spacetime wormholes in quantum gravity was analyzed in Sidney R. Coleman, "Black Holes as Red Herrings: Topological Fluctuations and the Loss of Quantum Coherence," *Nuclear Physics B* 307 (1988); Steven B. Giddings and Andrew Strominger, "Axion Induced Topology Change in Quantum Gravity and String Theory," *Nuclear Physics B* 306 (1988); and Steven B. Giddings and Andrew Strominger, "Loss of Incoherence and Determination of Coupling Constants in Quantum Gravity," *Nuclear Physics B* 307 (1988). Coleman's application of those ideas to address the CC problem is in Sidney R. Coleman, "Why There Is Nothing Rather than Something: A Theory of the Cosmological Constant," *Nuclear Physics B* 310 (1988).

Lenny's ambition, along with not finding evidence for a peak at zero CC, was realized in Willy Fischler, Igor Klebanov, Joseph Polchinski, and Leonard Susskind, "Quantum Mechanics of the Googolplexus," *Nuclear Physics B* 327 (1989).

The idea of addressing the CC problem by sourcing the CC with a four-form field strength was proposed in Stephen W. Hawking, "The Cosmological Constant Is Probably Zero," *Physical Letters B* 134 (1984). This is related to earlier work in Michael J. Duff and Peter van Nieuwenhuizen, "Quantum Inequivalence of Different Field Representations," *Physical Letters B* 94 (1980), and Antonio Aurilia, Hermann Nicolai, and Paul K. Townsend, "Hidden Constants: The Theta Parameter of QCD and the Cosmological Constant of N = 8 Supergravity," *Nuclear Physics B* 176 (1980).

Getting energy from tunneling was analyzed by Joe and collaborators in Willy Fischler, Daniel Morgan, and Joseph Polchinski, "Quantum Nucleation of False Vacuum Bubbles," *Physical Review D* 41 (1990), and Willy Fischler, Daniel Morgan, and Joseph Polchinski, "Quantization of False Vacuum Bubbles: A Hamiltonian Treatment of Gravitational Tunneling," *Physical Review D* 42 (1990). The general idea had been argued before in Edward Farhi and Alan H. Guth, "An Obstacle to Creating a Universe in the Laboratory," *Physical Letters B* 183 (1987).

Morgan's work on black holes with a cutoff placed on the maximum allowed curvature is Daniel Morgan, "Black Holes in Cutoff Gravity," *Physical Review D* 43 (1991).

The other possibilities for explaining the CC Joe mentions in passing are Tom Banks, "TCP, Quantum Gravity, the Cosmological Constant and All That . . . ," *Nuclear Physics B* 249 (1985); Laurence F. Abbott, "A Mechanism for Reducing the Value of the Cosmological Constant," *Physics Letters B* 150 (1985); J. David Brown and Claudio Teitelboim, "Dynamical Neutralization of the Cosmological Constant," *Physics Letters B* 195 (1987); and J. David Brown and Claudio Teitelboim, "Neutralization of the Cosmological Constant by Membrane Creation," *Nuclear Physics B* 297 (1988). Aspects of the latter two are discussed further in chapter 9.

Weinberg's seminal paper on bounding the CC using anthropics is Steven Weinberg, "Anthropic Bound on the Cosmological Constant," *Physical Review Letters* 59 (1987).

7.4

Work by Thorne and collaborators on closed time-like curves via boosted wormholes is Michael S. Morris, Kip S. Thorne, and Ulvi Yurtsever, "Wormholes, Time Machines, and the Weak Energy

Condition," *Physical Review Letters* 61 (1988). Their work studying the "Polchinski Paradox" of a billiard ball striking itself is Fernando Echeverria, Gunnar Klinkhammer, and Kip S. Thorne, "Billiard Balls in Wormhole Space-Times with Closed Timelike Curves: Classical Theory," *Physical Review D* 44 (1991).

Some problems with nonlinear extensions of quantum mechanics were studied by Joe in Joseph Polchinski, "Weinberg's Nonlinear Quantum Mechanics and the EPR Paradox," *Physical Review Letters* 66 (1991), and also in Nicolas Gisin, "Stochastic Quantum Dynamics and Relativity," *Helvetica Physica Acta* 62 (1989).

7.5

7.5.1 Attempts at defining string theory nonperturbatively include Edward Witten, "Noncommutative Geometry and String Field Theory," *Nuclear Physical B* 268 (1986); Ashoke Sen, "Tachyon Condensation on the Brane Anti-Brane System," *Journal of High Energy Physics* 8 (1998) (for a more recent review, see Ashoke Sen, "Tachyon Dynamics in Open String Theory," *International Journal of Modern Physics A* 20 [2005]); and Barton Zwiebach, "Closed String Field Theory: Quantum Action and the B-V Master Equation," *Nuclear Physics B* 390 (1993).

Work on solvable matrix models and 1 + 1-dimensional string theory is David J. Gross and Alexander A. Migdal, "Nonperturbative Two-Dimensional Quantum Gravity," *Physical Review Letters* 64 (1990); Michael R. Douglas and Stephen H. Shenker, "Strings in Less than One Dimension," *Nuclear Physics B* 335 (1990); and Edouard Brezin and Vladimir A. Kazakov, "Exactly Solvable Field Theories of Closed Strings," *Physical Letters B* 236 (1990).

The size of nonperturbative effects in string theory was studied in Stephen H. Shenker, "The Strength of Nonperturbative Effects in String Theory," in *The Large N Expansion in Quantum Field Theory and Statistical Physics: From Spin Systems to Two-Dimensional Gravity*, ed. E. Brezinand and S. R. Wadia (Singapore: World Scientific, 1993), 809–819.

7.5.2 Joe's work with Bryce on searching for a UV fixed point for quantum gravity was done in Jorge de Lyra, Bryce S. DeWitt, See Kit Foong, Timothy Gallivan, Rob Harrington, Arie Kapulkin, Eric Myers, and Joseph Polchinski, "The Quantized $O(1,2)$ / $O(2) \times Z(2)$ Sigma Model Has No Continuum Limit in Four-Dimensions. 1. Theoretical Framework," *Physical Review D* 46 (1992), and Jorge de Lyra, Bryce S. DeWitt, See Kit Foong, Timothy Gallivan, Rob Harrington, Arie Kapulkin, Eric Myers, and Joseph Polchinski, "The Quantized $O(1,2)$ / $O(2) \times Z(2)$ Sigma Model Has No Continuum Limit in Four-Dimensions. 2. Lattice Simulation," *Physical Review D* 46 (1992).

7.5.3 The quantum mechanics text that Joe used is A. S. Davydov, *Quantum Mechanics* (New York: Pergamon Press, 1965).

Joe's seminal paper on Fermi surfaces is Joseph Polchinski, "Effective Field Theory and the Fermi Surface," in *Recent Directions in Particle Theory: From Superstrings and Black Holes to the Standard Model*, Proceedings of the 1992 Theoretical Advanced Study Institute in Elementary Particle Physics, ed. Jeffrey Harvey and Joseph Polchinski (Singapore: World Scientific, 1993), 235–274.

7.6

The work on *T*-duality in time-dependent solutions is Eric Smith and Joseph Polchinski, "Duality Survives Time Dependence," *Physical Letters B* 263 (1991). Smith's work analyzing 1 + 1 strings is Eric Smith, "Light Cone Gauge for (1 + 1) Strings," *Nuclear Physics B* 382 (1992).

Minic's work on solutions to 1 + 1-dimensional string theory is in Djordje Minic, Joseph Polchinski, and Zhu Yang, "Translation Invariant Backgrounds in (1 + 1)-Dimensional String Theory," *Nuclear Physics B* 369 (1992), and Djordje Minic and Zhu Yang, "Is S = 1 for c = 1?," *Physical Letters B* 274 (1992). His work on quark dynamics is in Duane A. Dicus, Djordje Minic, Ubirajara van Kolck, and Roberto Vega, "The Axial Vector Coupling and Magnetic Moment of the Quark," *Physical Letters B* 284 (1992). The work on the Luttinger liquid is Djordje Minic, "On the Theory of the One-Dimensional Luttinger Liquid," *Modern Physical Letters B* 7 (1993). His work on 1 + 1-dimensional black holes is in Shyamoli Chaudhuri and Djordje Minic, "On the Black Hole Background of Two-Dimensional String Theory," *Physical Letters B* 312 (1993).

Natsuume's first project from Joe on noncritical strings is Makoto Natsuume, "Nonlinear Sigma Model for String Solitons," *Physical Review D* 48 (1993). His second on the high-dimensional string S-matrix is Makoto Natsuume, "Natural Generalization of Bosonic String Amplitudes," preprint, submitted February 26, 1993. https://arxiv.org/abs/hep-th/9302131. The work he did on the S-matrix in 1 + 1 dimensions is Makoto Natsuume, "Zero Mode Divergence Problem in String Theory," *Modern Physical Letters A* 9 (1994). His work on corrections to string theory black holes is Makoto Natsuume, "Higher Order Correction to the GHS String

Black Hole," *Physical Review D* 50 (1994). Including Joe, the work on gravity in the 1 + 1-dimensional string theory is Makoto Natsuume and Joseph Polchinski, "Gravitational Scattering in the c = 1 Matrix Model," *Nuclear Physics B* 424 (1994).

A list of Makoto's popular articles and books can be found on his personal website at https://research.kek.jp/people/natsuume/activities-e.html.

CHAPTER 8

8.1

A highly recommended resource for physicists, novice and veterans alike, is the KITP website https://www.kitp.ucsb.edu, which keeps an audio/video archive of all its conferences and workshops.

The rather amusing book on the history of the IAS is Ed Regis, *Who Got Einstein's Office? Eccentricity and Genius at the Institute for Advanced Study* (New York: Perseus Publishing, 1987).

8.2

Hawking's discovery that black holes evaporate via pair creation at the horizon is in Stephen W. Hawking, "Particle Creation by Black Holes," *Communications Mathematical Physics* 43 (1975). He then argued that it led to a loss of information in Stephen W. Hawking, "Breakdown of Predictability in Gravitational Collapse," *Physical Review D* 14 (1976).

The famous CGHS model of an evaporating black hole in two dimensions was introduced in Curtis G. Callan, Jr., Steven B. Giddings, Jeffrey A. Harvey, and Andrew Strominger, "Evanescent Black Holes," *Physical Review D* 45 (1992).

The papers that were inspired by the ITP program on the information paradox were Steven B. Giddings, Jeffrey A. Harvey, J. G. Polchinski, Stephen H. Shenker, and Andrew Strominger, "Hairy Black Holes in String Theory," *Physical Review D* 50 (1994), on the constructions of string theory black holes; Joseph Polchinski and Andrew Strominger, "A Possible Resolution of the Black Hole Information Puzzle," *Physical Review D* 50 (1994), on the role of baby universes in possibly resolving the paradox (see also Andrew Strominger, "Unitary Rules for Black Hole Evaporation," preprint, submitted October 26, 1994, https://arxiv.org/abs/hep-th/9410187); and David A. Lowe, Joseph Polchinski, Leonard Susskind, Larus Thorlacius, and John Uglum, "Black Hole Complementarity Versus Locality," *Physical Review D* 52 (1995), on the locality of string theory.

8.3

Joe's work with Matthew is Charles L. Kane, Matthew P. A. Fisher, and Joseph Polchinski, "Randomness at the Edge: Theory of Quantum Hall Transport at Filling $\nu = 2/3$," *Physical Review Letters* 72 (1994).

8.4

The important works that Joe recalls after the first superstring revolution are Gary T. Horowitz and Andrew Strominger, "Black Strings and P-Branes," *Nuclear Physics B* 360 (1991), on black branes; Anamaría Font, Luis E. Ibanez, Dieter Lüst, and Fernando Quevedo, "Strong–Weak Coupling Duality and Nonperturbative Effects in String Theory," *Physics Letters B* 249 (1990), on the weak/strong duality conjecture; Michael J. Duff, "Supermembranes: The

First Fifteen Weeks," *Classical and Quantum Gravity* 5 (1988), and Andrew Strominger, "Heterotic Solitons," *Nuclear Physics B* 343 (1990), on the 5-brane conjectures; John H. Schwarz and Ashoke Sen, "Duality Symmetric Actions," *Nuclear Physics B* 411 (1994), on duality effective actions; and Cumrun Vafa and Edward Witten, "A Strong Coupling Test of S Duality," *Nuclear Physics B* 431 (1994), and Nathan Seiberg, "Electric–Magnetic Duality in Supersymmetric Non-Abelian Gauge Theories," *Nuclear Physics B* 435 (1995), on similar analysis but in gauge theory.

According to Joe, the beginning of the second superstring revolution was Witten's unification of the superstring theories presented in Edward Witten, "String Theory Dynamics in Various Dimensions," *Nuclear Physics B* 443 (1995), and which built on earlier work in Christopher M. Hull and Paul K. Townsend, "Unity of Superstring Dualities," *Nuclear Physics B* 438 (1995). The refinement for the dual of the heterotic theory is in Petr Hořava and Edward Witten, "Heterotic and Type I String Dynamics from Eleven Dimensions," *Nuclear Physics B* 460 (1996).

8.5

Joe's catch-up work on K3s includes Shyamoli Chaudhuri and Joseph Polchinski, "Moduli Space of CHL Strings," *Physical Review D* 52 (1995), analyzing models developed earlier in Shyamoli Chaudhuri, George Hockney, and Joseph D. Lykken, "Maximally Supersymmetric String Theories in D < 10," *Physical Review Letters* 75 (1995), and Eric G. Gimon and Joseph Polchinski, "Consistency Conditions for Orientifolds and d Manifolds," *Physical Review D* 54 (1996), studying type I string compactifications.

Joe's seminal work outlining that D-branes carry RR flux is Joseph Polchinski, "Dirichlet Branes and Ramond-Ramond charges," *Physical Review Letters* 75 (1995).

Out of this came the counting of bound states of string and branes in Edward Witten, "Bound States of Strings and P-Branes," *Nuclear Physics B* 460 (1996); the connection between D-branes and instantons in Michael R. Douglas, "Branes within Branes," *NATO Science for Peace and Security Series C* 520 (1999), and Edward Witten, "Small Instantons in String Theory," *Nuclear Physics B* 460 (1996); the discovery of the duality between type I D1 branes and heterotic strings in Joseph Polchinski and Edward Witten, "Evidence for Heterotic–Type I String Duality," *Nuclear Physics B* 460 (1996); the laying-out of rules for branes ending on branes in Andrew Strominger, "Open P-Branes," *Physics Letters B* 383 (1996); and the connection between D-branes and M2-branes in Paul K. Townsend, "D-Branes from M-Branes," *Physics Letters B* 373 (1996), and John H. Schwarz, "The Power of M Theory," *Physics Letters B* 367 (1996).

The series of works involving Vafa is in Michael Bershadsky, Cumrun Vafa, and Vladimir Sadov, "D-Branes and Topological Field Theories," *Nuclear Physics B* 463 (1996); Cumrun Vafa, "Gas of D-Branes and Hagedorn Density of BPS States," *Nuclear Physics B* 463 (1996); Hirosi Ooguri and Cumrun Vafa, "Two-Dimensional Black Hole and Singularities of CY Manifolds," *Nuclear Physics B* 463 (1996); and Cumrun Vafa, "Instantons on D-Branes," *Nuclear Physics B* 463 (1996).

The scattering of D-branes was determined in Constatin Bachas, "D-brane Dynamics," *Physics Letters B* 374 (1996).

Joe's work with Strominger on D-branes and Calabi-Yau manifolds is in Joseph Polchinski and Andrew Strominger, "New Vacua for Type II String Theory," *Physics Letters B* 388 (1996).

The major breakthrough of assigning a statistical interpretation to the Bekenstein-Hawking entropy of a black hole was done in Andrew Strominger and Cumrun Vafa, "Microscopic Origin of the Bekenstein-Hawking Entropy," *Physics Letters B* 379 (1996).

CHAPTER 9

9.1

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His work on orientifolds and K3s is in Eric G. Gimon and Joseph Polchinski, "Consistency Conditions for Orientifolds and D Manifolds," *Physical Review D* 54 (1996); Micha Berkooz, Robert G. Leigh, Joseph Polchinski, John H. Schwarz, Nathan Seiberg, and Edward Witten, "Anomalies, Dualities, and Topology of D = 6 N = 1 Superstring Vacua," *Nuclear Physics B* 475 (1996); and Joseph Polchinski, "Tensors from K3 Orientifolds," *Physical Review D* 55 (1997).

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9.2

As was mentioned previously, the use of D-branes to calculate the microscopic density of states for supersymmetric black holes was shown in Andrew Strominger and Cumrun Vafa, "Microscopic Origin of the Bekenstein-Hawking Entropy," *Physics Letters B* 379 (1996). A similar analysis for ordinary nonsupersymmetric black holes was conducted by Joe and Horowitz in Gary T. Horowitz and Joseph Polchinski, "A Correspondence Principle for Black Holes and Strings," *Physical Review D* 55 (1997), which was followed up in Gary T. Horowitz and Joseph Polchinski, "Self-Gravitating Fundamental Strings," *Physical Review D* 57 (1998).

The analysis of probe branes interacting with a black hole or with its description as a stack of D-branes was done in Michael R. Douglas, Joseph Polchinski, and Andrew Strominger, "Probing Five-Dimensional Black Holes with D-Branes," *Journal of High Energy Physics* 12 (1997).

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Witten's recent work on the finiteness of string theory is in Edward Witten, "Notes on Supermanifolds and Integration," preprint, submitted September 11, 2012, https://arxiv.org/abs/1209.2199; Edward Witten, "Notes on Super Riemann Surfaces and Their Moduli," preprint, submitted September 11, 2012, https://arxiv.org/abs/1209.2459; and Edward Witten, "Superstring Perturbation Theory Revisited," preprint, submitted September 25, 2012, https://arxiv.org/abs/1209.5461. Work on this was also done by Sen around the same time and published in Ashoke Sen, "Off-Shell Amplitudes in Superstring Theory," *Fortschritte der Physik* 63 (2015).

The classic text on electromagnetism is none other than John David Jackson, *Classical Electrodynamics* (New York: Wiley, 1999).

9.4

The fifth wave of the second superstring revolution, AdS/CFT, was first proposed in Juan M. Maldacena, "The Large N Limit of Superconformal Field Theories and Supergravity," *Advances in Theoretical Mathematical Physics* 2 (1998).

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The question of extracting flat spacetime physics from AdS was investigated by Joe in Joseph Polchinski, "S Matrices from AdS Space-time," preprint, submitted January 18, 1999, https://arxiv.org/abs/hep-th/9901076, and also in Leonard Susskind, "Holography in the Flat Space Limit," in *AIP Conference Proceedings* 493, ed. C. P. Burgess and Rob Myers (College Park, MD: AIP Publishing, 1999), 98–112.

Understanding how scattering deep in the bulk in terms of the "precursor" was done in Joseph Polchinski, Leonard Susskind, and

Nicolaos Toumbas, "Negative Energy, Superluminosity and Holography," *Physical Review D* 60 (1999). This is related to previous work in Tom Banks, Michael R. Douglas, Gary T. Horowitz, and Emil J. Martinec, "AdS Dynamics from Conformal Field Theory," preprint, submitted August 4, 1998, https://arxiv.org/abs/hep-th/9808016, and Vijay Balasubramanian, Per Kraus, Albion E. Lawrence, and Sandip P. Trivedi, "Holographic Probes of Anti–de Sitter Space-Times," *Physical Review D* 59 (1999).

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The singularity resolutions of Joe and Strassler of naked singularities in AdS/CFT are in Joseph Polchinski and Matthew J. Strassler, "The String Dual of a Confining Four-Dimensional Gauge Theory," preprint, submitted March 15, 2000, https://arxiv.org/abs/hep-th/0003136, by employing the interesting behavior of D-branes with a background electromagnetic field that was discovered in Robert Myers, "Dielectric-Branes," *Journal of High Energy Physics* 12 (1999).

Other works with Strassler are Joseph Polchinski and Matthew J. Strassler, "Hard Scattering and Gauge/String Duality," *Physical Review Letters* 88 (2002), on reproducing results of boundary scattering using strings in the bulk; Joseph Polchinski and Matthew J. Strassler, "Deep Inelastic Scattering and Gauge/String Duality," *Journal of High Energy Physics* 5 (2003), on capturing the inelastic effects of boundary scattering; and Richard C. Brower, Joseph Polchinski, Matthew J. Strassler, and Chung-I Tan, "The Pomeron and Gauge/String Duality," *Journal of High Energy Physics* 12 (2007), on probing boundary scattering in Regge regime.

Joe's follow-up on these topics with Susskind is in Joseph Polchinski and Leonard Susskind, "String Theory and the Size of Hadrons," in *Bled 2000/2001, What Comes beyond the Standard Model* 1 (2001).

9.6

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CHAPTER 10

10.1

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Bulk of AdS(5) and other spaces," *Physical Review D* 62 (2000), and Iosif Bena, "The Propagator for a General Form Field in AdS(d+1)," *Physical Review D* 62 (2000); and his work generalizing Joe's work with Strassler is in Iosif Bena, "The M Theory Dual of a Three-Dimensional Theory with Reduced Supersymmetry," *Physical Review D* 62 (2000).

Graña's work with Joe rederiving his results with Strassler by finding supersymmetric AdS solutions with flux is Mariana Graña and Joseph Polchinski, "Supersymmetric Three Form Flux Perturbations on AdS(5)," *Physical Review D* 63 (2001). Her work on effective low energy supersymmetry breaking for D-branes is in Mariana Graña, "D3-Brane Action in a Supergravity Background: The Fermionic Story," *Physical Review D* 66 (2002), and Mariana Graña, "MSSM Parameters from Supergravity Backgrounds," *Physical Review D* 66 (2003). Graña's review of flux compactifications is Mariana Graña, "Flux Compactifications in String Theory: A Comprehensive Review," *Physics Reports* 423 (2006).

Frey's work on $N=1^*$ D-brane configurations is in Andrew R. Frey, "Brane Configurations of BPS Domain Walls for the $N=1^*$ SU(N) Gauge Theory," *Journal of High Energy Physics* 12 (2000). His work with Joe on $N=3$ warped compactifications is Andrew R. Frey and Joseph Polchinski, "$N=3$ Warped Compactifications," *Physical Review D* 65 (2002).

The idea of warped compactifications was proposed in the seminal works of Randall and Sundrum: Lisa Randall and Raman Sundrum, "A Large Mass Hierarchy from a Small Extra Dimension," *Physical Review Letters* 83 (1999), and Lisa Randall and Raman Sundrum, "An Alternative to Compactification," *Physical Review Letters* 83 (1999). The realization of this by Becker and Becker is in

Katrin Becker and Melanie Becker, "Compactifying M Theory to Four-Dimensions," *Journal of High Energy Physics* 11 (2000), and that of Strominger is in Andrew Strominger, "Superstrings with Torsion," *Nuclear Physics B* 274 (1986).

Frey's other papers include Alex Buchel and Andrew R. Frey, "Comments on Supergravity Dual of Pure N = 1 Super Yang-Mills Theory with Unbroken Chiral Symmetry," *Physical Review D* 64 (2001), on $N=1$ SUSY; Mariana Graña and Andrew R. Frey, "BPS States of Strings in Three Form Flux," *Physical Review D* 67 (2003), on BPS states; Andrew R. Frey and Anupam Mazumdar, "Three Form Induced Potentials, Dilaton Stabilization, and Running Moduli," *Physical Review D* 67 (2003), on dilaton stabilization; Andrew R. Frey, "String Theoretic Bounds on Lorentz Violating Warped Compactification," *Journal of High Energy Physics* 4 (2003), on Lorentz breaking in warped space; Andrew R. Frey, Matthew Lippert, and Brook Williams, "The Fall of Stringy de Sitter," *Physical Review D* 68 (2003) on instabilities of KKLT; and Andrew R. Frey, "Warped Strings: Self-Dual Flux and Contemporary Compactifications," preprint, submitted August 22, 2003, https://arxiv.org/abs/hep-th/0308156, on a new set of warped solutions.

10.2

References for the idea of warped compactifications can be found in the previous section. Verlinde's work demonstrating that warped compactifications arise from T-dualizing $N=4$ string theories is in Herman L. Verlinde, "Holography and Compactification," *Nuclear Physics B* 580 (2000). This was extended to $N=1$ by Joe and collaborators in Steven B. Giddings, Shamit Kachru, and Joseph

Polchinski, "Hierarchies from Fluxes in String Compactifications," *Physical Review D* 66 (2002).

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Joe's work with Silverstein and her student Adams on closed string tachyons is Alan Adams, Joseph Polchinski, and Eva Silverstein, "Don't Panic! Closed String Tachyons in ALE Space-Times," *Journal of High Energy Physics* 10 (2001). Sen's work on open string tachyons is in Ashoke Sen, "Non-BPS States and Branes in String Theory," preprint, submitted April 29, 1999, https://arxiv.org/abs/hep-th/9904207.

10.4

10.4.1 The ekpyrotic universe model was proposed in Justin Khoury, Burt A. Ovrut, Paul J. Steinhardt, and Neil Turok, "The Ekpyrotic Universe: Colliding Branes and the Origin of the Hot Big Bang," *Physical Review D* 64 (2001). The model for null orbifold singularity resolution in string theory is in Hong Liu, Gregory W. Moore, and Nathan Seiberg, "Strings in a Time Dependent Orbifold," *Journal of High Energy Physics* 6 (2002), and Hong Liu, Gregory W. Moore, and Nathan Seiberg, "Strings in Time Dependent Orbifolds," *Journal of High Energy Physics* 10 (2002). The instability of this resolution once backreaction is taken into account is argued in Gary T. Horowitz and Joseph Polchinski, "Instability of Space-Like and Null Orbifold Singularities," *Physical Review D* 66 (2002).

10.4.2 The Weinberg-Witten theorem precluding the emergence of the graviton is proved in Steven Weinberg and Edward Witten, "Limits on Massless Particles," *Physics Letters B* 96 (1980). The model claiming to get an emergent graviton in one fewer dimension is in Shou-Cheng Zhang and Jiang-ping Hu, "A Four-Dimensional Generalization of the Quantum Hall Effect," *Science* 294 (2001), and Jiang-ping Hu and Shou-Cheng Zhang, "Collective Excitations at the Boundary of a 4-D Quantum Hall Droplet," *Physical Review B* 66 (2002). Joe's work with Elvang showing that what emerges isn't actually gravity is in Henriette Elvang and Joseph Polchinski, "The Quantum Hall Effect on R**4," preprint, submitted September 12, 2002, https://arxiv.org/abs/hep-th/0209104.

10.4.3 Studying the string world sheet theory with $AdS_5 \times S^5$ target space was analyzed in Iosif Bena, Joseph Polchinski, and Radu Roiban, "Hidden Symmetries of the AdS(5) × S**5 Superstring," *Physical Review D* 69 (2004), for the superstring, and in Gautam Mandal, Nemani V. Suryanarayana, and Spenta R. Wadia, "Aspects of Semiclassical Strings in AdS(5)," *Physics Letters B* 543 (2002), for the bosonic string. The method of finding the infinite symmetry algebras in nonlinear sigma models is devised in Martin Luscher and Klaus Pohlmeyer, "Scattering of Massless Lumps and Nonlocal Charges in the Two-Dimensional Classical Nonlinear Sigma Model," *Nuclear Physics B* 137 (1978).

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Joe's work with Mann on understanding better the symmetry in an integrable theory is in Nelia Mann and Joseph Polchinski, "Finite Density States in Integrable Conformal Field Theories," in *From Fields to Strings: Circumnavigating Theoretical Physics*, ed. M. Shifman, A. Vainshtein, and J. Wheater (Singapore: World Scientific, 2004), 1365–1383, and in Nelia Mann and Joseph Polchinski, "Bethe Ansatz for a Quantum Supercoset Sigma Model," *Physical Review D* 72 (2005).

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10.6

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Joe's work with Rocha on the scale of the cosmic strings is in Joseph Polchinski and Jorge V. Rocha, "Analytic Study of Small

Scale Structure on Cosmic Strings," *Physical Review D* 74 (2006), and on the scale of the gravitational waves is in Joseph Polchinski and Jorge V. Rocha, "Cosmic String Structure at the Gravitational Radiation Scale," *Physical Review D* 75 (2007); further work including Dubath is in Florian Dubath, Joseph Polchinski, and Jorge V. Rocha, "Cosmic String Loops, Large and Small," *Physical Review D* 77 (2008). The numerical simulations of these cosmic strings is in Jose J. Blanco-Pillado, Ken D. Olum, and Benjamin Shlaer, "The Number of Cosmic String Loops," *Physical Review D* 89 (2014).

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Joe's work on the open string in the heterotic SO(32) theory is in Joseph Polchinski, "Open Heterotic Strings," *Journal of High Energy Physics* 9 (2006).

10.7

Smolin's book that Joe is very critical of is Lee Smolin, *The Trouble with Physics: The Rise of String Theory, the Fall of a Science, and What Comes Next* (Boston: Houghton Mifflin, 2006). Joe's take on the book and the thesis of the book can be found in Joseph Polchinski, "All Strung Out?," *American Scientist* 95, no. 1 (2007): 72, https://www.americanscientist.org/article/all-strung-out. Smolin's response can be found at: https://www.kitp.ucsb.edu/joep/links/some-criticisms-string-theory/lee-smolins-response.

CHAPTER 11

11.1

Joe's work with Arkani-Hamed and Orgera on realizing Euclidean wormholes with known boundary duals is in Nima Arkani-Hamed, Jacopo Orgera, and Joseph Polchinski, "Euclidean Wormholes in String Theory," *Journal of High Energy Physics* 12 (2007). They showed that such solutions are inconsistent with properties that boundary duals should have, based on arguments by Rey in Soo-Jong Rey, "Holographic Principle and Topology Change in String Theory," *Classical Quantum Gravity* 16 (1999).

Maldacena's recasting of the information paradox as the exponential decay of the two-point function is in Juan M. Maldacena, "Eternal Black Holes in Anti–de Sitter," *Journal of High Energy Physics* 4 (2003). The toy model by Festuccia and Liu is in Guido Festuccia and Hong Liu, "The Arrow of Time, Black Holes, and Quantum Mixing of Large N Yang-Mills Theories," *Journal of High Energy Physics* 12 (2007). The simple matrix model of Joe and Iizuka displaying these same features is in Norihiro Iizuka and Joseph Polchinski, "A Matrix Model for Black Hole Thermalization," *Journal of High Energy Physics* 10 (2008), which was then followed up in Norihiro Iizuka, Takuya Okuda, and Joseph Polchinski, "Matrix Models for the Black Hole Information Paradox," *Journal of High Energy Physics* 2 (2010), providing models that could be studied analytically.

The table of integrals that Joe often refers to is in I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products* (Orlando, FL: Academic Press, 1965, 1980).

The instability of nonsupersymmetric orbifolds was analyzed in Gary T. Horowitz, Jacopo Orgera, and Joseph Polchinski, "Nonperturbative Instability of AdS(5) × S**5/Z(k)," *Physical Review D* 77 (2008); they were found to be susceptible to bubbles of nothing, studied in Edward Witten, "Instability of the Kaluza-Klein Vacuum," *Nuclear Physics B* 195 (1982).

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11.2

Penedones's work with Gary and Giddings on the flat space limit of AdS scattering is in Mirah Gary, Steven B. Giddings, and Joao Penedones, "Local Bulk S-Matrix Elements and CFT Singularities," *Physical Review D* 80 (2009). This analysis was then developed into a "derivation" of AdS/CFT by studying the four-point function in Idse Heemskerk, Joao Penedones, Joseph Polchinski, and James Sully, "Holography from Conformal Field Theory," *Journal of High Energy Physics* 10 (2009).

The interpretation of the scale-radius relation in AdS/CFT in terms of Wilsonian RG was done in Thomas Faulkner, Hong Liu, and Mukund Rangamani, "Integrating Out Geometry: Holographic Wilsonian RG and the Membrane Paradigm," *Journal of High Energy Physics* 8 (2011), and by Joe and Heemskerk in Idse Heemskerk and Joseph Polchinski, "Holographic and Wilsonian Renormalization Groups," *Journal of High Energy Physics* 6 (2011). The application of this to "higher spin" theories by Joe and Mintun is in Eric Mintun and Joseph Polchinski, "Higher Spin Holography, RG, and the Light Cone," preprint, submitted November 12, 2014, https://arxiv.org/abs/1411.3151.

11.3

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Joe's work on the AdS/CM with Lifshitz symmetry instead of purely AdS is in Sean A. Hartnoll, Joseph Polchinski, Eva Silverstein, and David Tong, "Towards Strange Metallic Holography," *Journal of High Energy Physics* 4 (2010). The different approach to high-T_c/CFT using two-dimensional AdS was pursued in Thomas Faulkner, Hong Liu, John McGreevy, and David Vegh, "Emergent Quantum Criticality, Fermi Surfaces, and AdS(2)," *Physical Review D* 83 (2011). The method of getting the universal behavior is in Thomas Faulkner and Joseph Polchinski, "Semi-Holographic Fermi Liquids," *Journal of High Energy Physics* 6 (2011).

The other models involving branes corresponding to a lattice and itinerant charges was proposed in Kristan Jensen, Shamit Kachru, Andreas Karch, Joseph Polchinski, and Eva Silverstein, "Towards a Holographic Marginal Fermi Liquid," *Physical Review D* 84 (2011).

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Joe's work with Silverstein on interpreting the vacuum state as a finite-density system in higher dimensions and realizing "$2k_F$"

singularities of Fermi and non-Fermi liquids was done in Joseph Polchinski and Eva Silverstein, "Large-Density Field Theory, Viscosity, and '$2k_F$' Singularities from String Duals," *Classical and Quantum Gravity* 29 (2012).

11.4

11.4.1 Joe's work with Silverstein on constructing solutions where the size of the AdS radius is much larger than the compactification radius is in Joseph Polchinski and Eva Silverstein, "Dual Purpose Landscaping Tools: Small Extra Dimensions in AdS/CFT," preprint submitted August 5, 2009, https://arxiv.org/abs/0908.0756.

11.4.2 The work showing that a BPS Wilson loop on the boundary is dual to a string worldsheet ending on the loop was done in Soo-Jong Rey and Jung-Tay Yee, "Macroscopic Strings as Heavy Quarks in Large N Gauge Theory and Anti–de Sitter Supergravity," *European Physical Journal C* 22 (2001), and Juan M. Maldacena, "Wilson Loops in Large N Field Theories," *Physical Review Letters* 80 (1998). The extension to a normal Wilson loop was pursued by Joe and Sully in Joseph Polchinski and James Sully, "Wilson Loop Renormalization Group Flows," *Journal of High Energy Physics* 10 (2011), much of which was previously noted in Luis F. Alday and Juan M. Maldacena, "Comments on Gluon Scattering Amplitudes via AdS/CFT," *Journal of High Energy Physics* 11 (2007).

11.4.3 Extension of Zamolodchikov's result of the irreversibility RG to four dimensions was done in Zohar Komargodski and Adam Schwimmer, "On Renormalization Group Flows in Four Dimensions," *Journal of High Energy Physics* 12 (2011). This result was then used to show that, at least perturbatively, scale invariance does lead to conformal invariance in Markus A. Luty, Joseph Polchinski, and Riccardo Rattazzi, "The *a*-theorem and the Asymptotics of 4D Quantum Field Theory," *Journal of High Energy Physics* 1 (2013). The supposed counterexample was announced in Jean-Francois Fortin, Benjamin Grinstein, and Andreas Stergiou, "Scale without Conformal Invariance: An Example," *Physics letters B* 704 (2011), although this group ultimately came around and agreed with Joe and collaborators in Jean-Francois Fortin, Benjamin Grinstein, and Andreas Stergiou, "Limit Cycles and Conformal Invariance," *Journal of High Energy Physics* 1 (2013).

CHAPTER 12

12.1

The idea of extracting the physics inside the horizon by integrating it out all the way to the boundary was done in Idse Heemskerk, Donald Marolf, Joseph Polchinski, and James Sully, "Bulk and Transhorizon Measurements in AdS/CFT," *Journal of High Energy Physics* 10 (2012). This builds on previous work in Alex Hamilton, Daniel N. Kabat, Gilad Lifschytz, and David A. Lowe, "Local Bulk Operators in AdS/CFT: A Boundary View of Horizons and Locality," *Physical Review D* 73 (2006), and Alex Hamilton, Daniel N. Kabat, Gilad Lifschytz, and David A. Lowe, "Holographic Representation of Local Bulk Operators," *Physical Review D* 74 (2006). The extension to include gauge fields was worked out by Heemskerk in Idse Heemskerk, "Construction of Bulk Fields with Gauge Redundancy," *Journal of High Energy Physics* 9 (2012).

12.2

The simplified models of black hole evaporation devised to sharpen the paradox were investigated in Samir D. Mathur, "The Information Paradox: A Pedagogical Introduction," *Classical and Quantum Gravity* 26 (2009), and Steven B. Giddings, "Models for Unitary Black Hole Disintegration," *Physical Review D* 85 (2012). The heavy integration of quantum information concepts into the physics of black holes was pioneered in Patrick Hayden and John Preskill, "Black Holes as Mirrors: Quantum Information in Random Subsystems," *Journal of High Energy Physics* 9 (2007), with several surprising constraints on how black holes as unitary quantum systems should behave. These considerations led to the work of AMPS in Ahmed Almheiri, Donald Marolf, Joseph Polchinski, and James Sully, "Black Holes: Complementarity or Firewalls?," *Journal of High Energy Physics* 2 (2013).

12.3

Previous proposals on the need to modify the interior of black holes is in George Chapline, Evan Hohlfeld, Robert B. Laughlin, and David I. Santiago, "Quantum Phase Transitions and the Breakdown of Classical General Relativity," *International Journal of Modern Physics A* 18 (2003), and Pawel O. Mazur and Emil Mottola, "Surface Tension and Negative Pressure Interior of a Non-Singular 'Black Hole,'" *Classical and Quantum Gravity* 32 (2015). The work by Braunstein with conclusions resembling AMPS is in Samuel L. Braunstein, "Better Late than Never: Information Retrieval from Black Holes," *Physical Review Letters* 110 (2013).

A review of fuzzballs and their connection to the information paradox is Samir Mathur, "Fuzzballs and the Information Paradox:

A Summary and Conjectures," preprint, submitted February 6, 2014, last revised October 24, 2008, https://arxiv.org/abs/0810.4525.

12.4

Susskind has been concerned with connecting the complexity of the quantum state of a black hole to the nature of the black hole horizon and the size of its interior. See, for example, Leonard Susskind, "Computational Complexity and Black Hole Horizons," *Fortschritte der Physik* 64 (2016).

The extension and refinement of the AMPS argument was done in Ahmed Almheiri, Donald Marolf, Joseph Polchinski, Douglas Stanford, and James Sully, "An Apologia for Firewalls," *Journal of High Energy Physics* 9 (2013). Joe followed this up with Marolf in Donald Marolf and Joseph Polchinski, "Gauge/Gravity Duality and the Black Hole Interior," *Physical Review Letters* 111 (2013), where they addressed the question of whether the firewall invalidated Hawking's calculation for the radiation.

The "quantum drama" alternatives are the following: the final state proposal where the singularity implements a projection that postselects the combined quantum state of the interior radiation and matter, proposed in Gary T. Horowitz and Juan M. Maldacena, "The Black Hole Final State," *Journal of High Energy Physics* 2 (2004), and further analyzed in Seth Lloyd and John Preskill, "Unitarity of Black Hole Evaporation in Final-State Projection Models," *Journal of High Energy Physics* 8 (2014); the limitation of possible quantum computations within the lifetime of the black hole put forth in Daniel Harlow and Patrick Hayden, "Quantum Computation vs. Firewalls," *Journal of High Energy Physics* 6

(2013); the possibility that quantum entanglement can lead wormholes connecting the interior to the faraway radiation proposed in Juan Maldacena and Leonard Susskind, "Cool Horizons for Entangled Black Holes," *Fortschritte der Physik* 61 (2013); and the idea that the physics of the interior of the black hole is represented by nonlinear state-dependent operators proposed in Kyriakos Papadodimas and Suvrat Raju, "An Infalling Observer in AdS/CFT," *Journal of High Energy Physics* 10 (2013), and in Erik Verlinde and Herman Verlinde, "Black Hole Entanglement and Quantum Error Correction," *Journal of High Energy Physics* 10 (2013). Joe and Marolf demonstrate how the last proposal can lead to large violations of the Born rule in Donald Marolf and Joseph Polchinski, "Violations of the Born Rule in Cool State-Dependent Horizons," *Journal of High Energy Physics* 1 (2016).

Other proposals include possible effects from strings as studied in Eva Silverstein, "Backdraft: String Creation in an Old Schwarzschild Black Hole," preprint, submitted February 6, 2014, last revised February 21, 2014, https://arxiv.org/abs/1402.1486, and possible nonlocal interactions between the inside and outside to extract the information as proposed in Steven B. Giddings, "Nonviolent Nonlocality," *Physical Review D* 88 (2013).

12.5

Joe's work with Sun and Mintun on the effective theory of intersecting D-branes is in Eric Mintun, Joseph Polchinski, and Sichun Sun, "The Field Theory of Intersecting D3-branes," *Journal of High Energy Physics* 8 (2015). The renormalization of field theories with brane defects was studied in Walter D. Goldberger and Mark B. Wise, "Renormalization Group Flows for Brane Couplings," *Physical*

Review D 65 (2002). This understanding was then extended by Joe and his collaborators to analyze the stability of KKLT in Ben Michel, Eric Mintun, Joseph Polchinski, Andrea Puhm, and Philip Saad, "Remarks on Brane and Antibrane Dynamics," *Journal of High Energy Physics* 9 (2015).

Extending the understanding of how fuzzballs, a certain kind of stack of D-branes, can be represented by different geometries in different limits was studied by Joe and collaborators in Fang Chen, Ben Michel, Joseph Polchinski, and Andrea Puhm, "Journey to the Center of the Fuzzball," *Journal of High Energy Physics* 2 (2015). A similar exercise was done previously in a different context in Emil J. Martinec and Vatche Sahakian, "Black Holes and Five-Brane Thermodynamics," *Physical Review D* 60 (1999).

12.6

The remarkable geometrization of boundary entanglement entropy as a bulk geometric property was first proposed in Shinsei Ryu and Tadashi Takayanagi, "Holographic Derivation of Entanglement Entropy from AdS/CFT," *Physical Review Letters* 96 (2006).

Resolving the density of states issue in holography with two bulk dimensions via backreaction was studied by Joe and Almheiri in Ahmed Almheiri and Joseph Polchinski, "Models of AdS_2 Backreaction and Holography," *Journal of High Energy Physics* 11 (2015).

The most basic element of the bulk boundary map of equating asymptotic local bulk fields to local operators in the CFT was proposed in Steven S. Gubser, Igor R. Klebanov, and Alexander M. Polyakov, "Gauge Theory Correlators from Noncritical String Theory," *Physics Letters B* 428 (1998), and Edward Witten, "Anti–de Sitter Space and Holography," *Advances in Theoretical and*

Mathematical Physics 2 (1998). The new understanding of the dictionary between the bulk and the boundary in terms of quantum error correction was first introduced in Ahmed Almheiri, Xi Dong, and Daniel Harlow, "Bulk Locality and Quantum Error Correction in AdS/CFT," *Journal of High Energy Physics* 4 (2015). The connection of this idea to gauge symmetry was proposed by Joe, Mintun, and Rosenhaus in Eric Mintun, Joseph Polchinski, and Vladimir Rosenhaus, "Bulk-Boundary Duality, Gauge Invariance, and Quantum Error Correction," *Physical Review Letters* 115 (2015).

Stanford and Shenker's work on the butterfly effect for perturbed eternal black holes was pioneered in Stephen H. Shenker and Douglas Stanford, "Black Holes and the Butterfly Effect," *Journal of High Energy Physics* 3 (2014). Maldacena's recasting of the AdS eternal black hole as the thermofield double state of the boundary builds on the earlier work of Israel making this connection for general equilibrium black holes in Werner Israel, "Thermo Field Dynamics of Black Holes," *Physics Letters A* 57 (1976).

't Hooft's analysis of gravitational scattering involving black holes is in Gerard 't Hooft, "The Scattering Matrix Approach for the Quantum Black Hole: An Overview," *International Journal of Modern Physics A* 11 (1996). Joe's work on the subject and connecting it to the butterfly effect for scattering of an infalling particle with the Hawking radiation is in Joseph Polchinski, "Chaos in the Black Hole S-matrix," preprint, submitted May 29, 2015, https://arxiv.org/abs/1505.08108.

Kitaev first publicly proposed his model exhibiting features of two-dimensional black holes in "A Simple Model of Quantum Holography" (https://online.kitp.ucsb.edu/online/entangled15/kitaev; https://online.kitp.ucsb.edu/online/entangled15/kitaev2).

The details of his proposal were later worked out and extended in Juan M. Maldacena and Douglas Stanford, "Remarks on the Sachdev-Ye-Kitaev Model," *Physical Review D* 94 (2016). The renewed analysis of old models of Joe, Iizuka, and Okuda on the simple matrix models was done in Ben Michel, Joseph Polchinski, Vladimir Rosenhaus, and S. Josephine Suh, "Four-Point Function in the IOP Matrix Model," *Journal of High Energy Physics* 5 (2016). Joe and Rosenhaus also filled in and extended Kitaev's results in Joseph Polchinski and Vladimir Rosenhaus, "The Spectrum in the Sachdev-Ye-Kitaev Model," *Journal of High Energy Physics* 4 (2016). Rosenhaus's extension of the SYK model with Gross is in David J. Gross and Vladimir Rosenhaus, "A Generalization of Sachdev-Ye-Kitaev," *Journal of High Energy Physics* 2 (2017).

The large collaboration involving Joe on the numerical analysis of the SYK model is Jordan S. Cotler, Guy Gur-Ari, Masanori Hanada, Joseph Polchinski, Phil Saad, Stephen H. Shenker, Douglas Stanford, Alexandre Streicher, and Masaki Tezuka, "Black Holes and Random Matrices," *Journal of High Energy Physics* 5 (2017). Erratum: *Journal of High Energy Physics* 9 (2017).