2 CALTECH, 1971–1975

2.1 ARRIVAL

The information available to college applicants today of course dwarfs what we had then. For me, the principal sources were *Reader's Digest* and the *World Almanac* and *Book of Facts*, but these were enough. A few years before college, I read a *Reader's Digest* article about the famous Caltech Rose Bowl prank.

The Washington team had planned a show in which several thousand fans in the stands would manipulate a set of cards, producing stadium-sized images. This went well until the last two cards, when *Huskie* was replaced by *Beaver*, and then *Washington* was replaced by *Caltech*. This had required an elaborate scheme by the Techers, culminating on the night before the game, when they replaced the thousands of individualized instructions. The article also mentioned the unique scientific environment of Caltech.

Having never heard of this place before, I went to my other source, the *Almanac*. It had a nice table of colleges, from which I learned that the student/faculty ratio at Caltech was around 2:1, compared with 20:1 at any other college. Pranks and top faculty—I was hooked. I never even read up about other schools—probably a lack of common sense, but it worked out this time. I applied to Caltech on early decision, and then waited with bated breath. Coming from a small school in a small state, I had no idea of where I stood. But when the letter came it was positive, and I sat back and laughed for a long time. This is what I had been waiting for.

So, in September of 1971, my family drove up from Tucson. This was a good day's drive, but my parents both enjoyed driving. And so we rolled up to my dorm, Blacker House, where I would spend the next four school years. We said goodbye, my mother crying on one of the few occasions I can remember, and my new life began.

2.2 ZAJC

During my first week on campus, I met three remarkable people: Richard Feynman, Kip Thorne, and William (Bill) Zajc. Feynman had won the Nobel Prize when I was still in grade school, more than fifty years ago now. Thorne may win the Nobel Prize next year.[1] Zajc, who is probably least known to most of you, is a distinguished scientist as well. He led the development of the PHENIX heavy ion detector at Brookhaven. This may not lead to a Nobel Prize (though who knows?), but it did reveal a connection between the entropy in nuclear physics and that in string theory. At the time we met, Feynman was a star, Thorne was a rising young star, and Zajc was, like me, a young whippersnapper first setting foot on the Caltech campus.

Zajc, like me, was in Blacker House, so we met on day one. Almost as quickly, he had an enormous effect on my life. As I've noted, I left high school with no knowledge of what physics really is. But at Caltech, I was immersed in it. Zajc was a big part of this. In high school in Wisconsin, he had already read some of *The Feynman Lectures*, Feynman's three-volume introduction to physics. In fact, this was to be used as the course for the advanced track for introductory physics. So Zajc got to Caltech with a much clearer picture of what physics was.

Zajc was outgoing (for a Techer), and he loved to talk about physics. I quickly learned what I had been missing. As Zajc told me amazing facts, and we worked through some key equations, I could see for the first time how calculus and physics fit together. I saw that this was what I was designed for. I had brought my chessboard with me to school, planning to practice an hour a day, but it was never opened.

For four years Bill and I took most of the same classes, working together as we learned physics. But as much as the physics, I remember the ways that Bill, our other friends, and I blew off steam in between. These included drives for Tommy's burgers and various sports. A group of us became avid cyclists, riding to the beach at Santa Monica and exploring LA on rides as long as a century (100 miles). Our special challenge was the ride to the top of Mount Wilson.

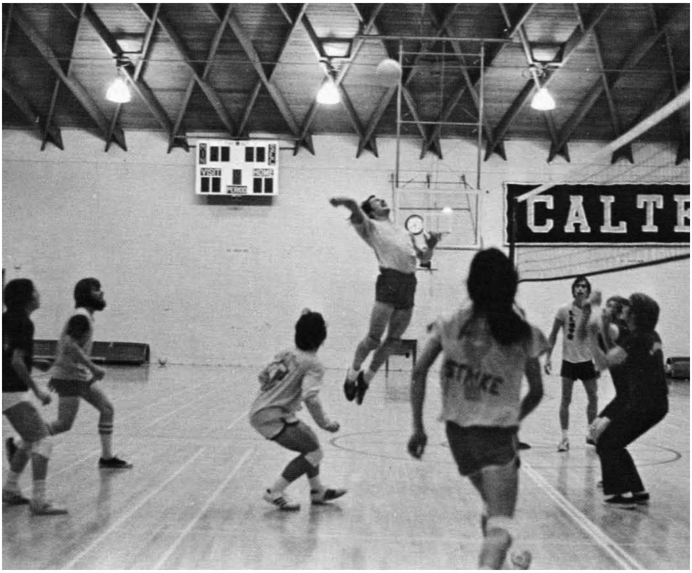


Figure 2.1
Volleyball at Caltech, ca. 1974. Courtesy of Caltech Big T.

2.3 PRANKS

Exploring the Caltech campus to discover its secrets was another pastime. At the most benign, this meant wandering the hallways of physics and other departments to see what went on there. More interesting were the nighttime excursions, clambering into construction sites, negotiating Caltech's elaborate steam-tunnel network, or simply applying the knowledge of lock-picking that had been passed down from generation to generation of Tech students (the physics building, Bridge, was known to be particularly easy). Finding some interesting, perhaps historic, piece of scientific equipment was a Prize.

In this way we carried out (though not on the scale of the Rose Bowl!) the kind of pranks that first lured me there. Our most notable one involved the roof of the library. The Caltech library, at nine stories, loomed over the campus. It was a natural location for undergraduate activities, which usually involved throwing, or floating, objects that may or may not have been flammable, from the roof. The door to the roof was locked, but this could be picked by the more talented Techers.

Caltech security did not think this was a good thing, and so the lock was replaced by an “unpickable” one. Indeed, our best locksmiths could not open it. This was an outrage, and a Plan B was necessary. There was a ventilation shaft nearby, opening on each floor and then out on the roof. The frame could be unscrewed, so all that was needed was someone with no common sense to climb the shaft from the top floor to the roof. Having a particular talent in this area, late one night I found myself wriggling up the last twelve feet of the shaft, with nine stories beneath me and tethered by a climbing rope that I had never tried. Fortunately, it was an easy climb, aside from a tense moment when I was stuck and unable to move in either direction. I got to the top and opened the door from the back.

Having defeated the unpickable lock, we had to celebrate. We removed the door from its hinges, and a dozen of us carried it down to the library basement and then through the underground steam tunnels to the Caltech security office. The lock-pick experts opened the office and we left the door, but only after the group of us, including Zajc and me, signed it. This might seem to be a foolish thing, but we knew that Security understood Techers and

Figure 2.2
Caltech prank, with Joe to the left of the door, holding it up, ca. 1974. Courtesy of Caltech Big T.

was easy on us; in fact, there ended up being no penalty at all. (Warning: Things are different now. Do not attempt.) And there was a nice bonus. Security replaced the door without removing or covering our signatures. So as of a few years ago, forty years after the fact, my signature, Zajc's, and the others (with maybe a fake or two) could still be seen on the door to the library roof.

2.4 FEYNMAN

I first met Feynman as an idol, not a person. In the courtyard of Dabney house, next to Blacker, a large bas-relief depicting the great scientists of history had been built many years before. When Feynman was awarded the Nobel Prize with Julian Schwinger and Sinichiro Tomonaga in 1965, the Dabney students replaced the dominating figure of Galileo with that of Feynman. Thus, we were surrounded by Feynman all the time, from his image, his books, and many other reminders. For many of us, Feynman was who we wanted to be.

I got a chance to meet the man himself before too long. Once a week, Feynman led Physics X, where freshman and sophomores could ask their questions about physics, or if we ran out of questions he would talk about some of his ideas. One example of this was, how do you take the square root of the Fourier transformation, so that acting on a function twice with the operation would be the same as the Fourier transform? For those interested, the answer is in the footnote,[2] but try it first. This kind of happy creativity was fascinating to see. Another question was, what is a negative probability? Unfortunately, my main contribution to the class was falling asleep one day, in the front row, which has delighted some of my classmates to this day.

One of the notable sights in Bridge Hall was a pair of small objects, a miniature page of text and a miniature motor. Both were inspired by Feynman's lecture "There's Plenty of Room at the Bottom." He foresaw the smaller and smaller scales that physics and technology could reach. In addition to his powerful calculational ability and his outsized personality, Feynman's ability to think far outside the box was awesome. Another example was the idea of quantum computation, where the "Plenty of Room" comes from, not from space but from Hilbert space.

So, many of us wanted to emulate Feynman. As I began to stand out in my classes, a couple of my classmates proclaimed me the next Feynman. I was happy to hear this, of course, but I knew better. In contrast to Feynman's striking originality, I have always felt myself to be weak in this area. This is not just me being self-effacing; you can judge it as we go along, but my impulse has simply been to follow my nose.

I was too shy to take more advantage of the time with Feynman, though I saw him often on that small campus. I did hear his stories at one faculty party, some of the same stories that later appeared in his book. Most exciting, when we were seniors, Zajc and I, along with two other seniors, were asked to grade Feynman's junior quantum mechanics homework. My strongest memory of the class is the very beginning, when he started, not with some deep principle of nature, or some experiment, but with a review of Gaussian integrals. Clearly, there was some calculating to be done.

I did get over my shyness one time, to ask him about the infinities that appear in quantum field theory (QFT): do they have a physical interpretation? Feynman said "no." In retrospect, he must have known more, from the work of Wilson, Weinberg, and others. But perhaps it did not satisfy him, since he had not derived it himself. But this question tugged on me for the next eight years, and was my first deep result.[3]

2.5 THORNE

Kip Thorne was my designated freshman advisor, so we met every quarter. His first order when I went to his office was "Call me Kip." This I could not do, so I spent the year addressing him without using his name.

Thorne's office door was covered with interesting artifacts. Most notable was a bet between Kip and Stephen Hawking, as to whether the radio source Cygnus X-1 was a black hole: Thorne bet yes, and Hawking no. If yes, it would be the first confirmed black hole in nature. Actually, both wanted, and expected, the answer to be yes, but Hawking was covering his bet: if he was disappointed by the black hole, at least he'd win a magazine subscription from Thorne. But indeed it was soon confirmed.

Thorne was a leader in general relativity, with a particular interest in the rich astrophysics of black holes. This required a team, so one always saw him with a group of enthusiastic grad students and postdocs. As we have seen, when Thorne began, black holes were still theoretical, though the theory was compelling. Soon there was Cygnus X-1, and in time an enormous number more, from quasars down to collapsed stars. Most recently, Thorne capped off his remarkable career as one of the leaders of the LIGO project. This billion-dollar experiment gave the first observation of gravitational radiation, predicted nearly one hundred years ago, and the first observation of coalescing black holes.

I did not have much interaction with Thorne as a student, aside from auditing his general relativity class. The research was too advanced for an undergrad. I did have an interesting science/sci-fi interaction with him several years later, which I will get to.

2.6 CLASSES

Thus, surrounded by these and many other outstanding scientists, my education went forward. The Feynman lectures were one of the highlights of the first two years. They were not perfect: as with everything Feynman did, he redid the subject from his own approach. This was inspiring, but challenging. There was a shortage of examples and calculations, but these were supplemented by a set of problems authored by two other high-level professors, Robert Leighton and Rochus Vogt.

There were also a variety of other subjects: astronomy, chemistry, advanced calculus, electronics. I took too many courses; this was common at Caltech. There was so much to learn, one wanted to cram it all in. Happily, only one nonscience course per quarter was required. In my four years I did not take much math: advanced calculus, complex variables, and a course on group theory that I again failed to grasp. I think I was influenced by an offhand remark from Feynman that one did not need to know much math, but it worked for me.

2.7 TOMBRELLO

Having so much fun in school, I did not want to leave during the summers. Today, undergraduate research is expected, but back then it was more hit-or-miss. Happily, Tom Tombrello was there. Tombrello was a nuclear and atomic physicist, working in particular on measuring the nuclear decay rates needed to understand the formation of the chemical elements. He was also a remarkable people person. When he saw that four of the top physics students (Bill, me, Roland Lee, and Ken Jancaitis) were looking for research projects, he took all of us on!

This was heaven: four of us sharing a basement office in Bridge, with a modest stipend, talking physics all day and unwinding at night. And Tombrello did not just put the four of us on some large project. We each had our own problem (which might be part of some larger collaboration), coming from Tom's many interests.

Over time I worked on estimation of waveguide shapes, calculating nuclear decay rates, and finding methods to study intermediate energy atomic collisions. He even showed one of my plots to Hawking when he was visiting Caltech.

Tombrello was one of the rare physicists who did both theory and experiment. He used the Van de Graff generator to study nuclear interactions, and so I got some time learning to run that. He also guided my senior thesis, attempting to zone-refine gallium in order to detect solar neutrinos.

Tombrello told me I should follow his path, and that of Fermi, doing both experiment and theory. But I was set on theory by nature. I remember spending a few hours moving some lead blocks with Tom, and thinking I did not want to spend my career moving lead blocks. But of course theory has its own drudgery, such as searching for factors of two. But I may have disabused Tom when I managed to break both the multichannel analyzer and some expensive glassware on my senior project.

Even after graduation, Tombrello kept in touch. He sent me a copy of Hawking's information paradox paper, written while a guest at Caltech, together with a note: "Joe, you should work on this!" He was right, but it took me a few years to get there.

Tombrello took a break after the four of us graduated, but several years later he instituted Physics 11 as a regular undergraduate research course. Tom passed away unexpectedly a few years ago. At his memorial, it was remarkable to hear about all the aspects of his life. The number of people he had affected, and especially his talent for bringing people together, was wonderful to hear about.

2.8 QFT, GR, QCD

Senior year, physics got even more interesting. I took QFT from Frautschi, and general relativity from Thorne. I did not end up with a good grasp of either subject. These days it is rather routine for seniors in theoretical physics to take these courses, but the subjects then were more difficult.

QFT was undergoing rapid development, and the textbooks had not yet caught up. The two volumes of Bjorken and Drell were the texts of general choice. This was a beautiful book when it was written, but ten eventful years had gone by, and a new text was needed.

General relativity did have a new text, and that was the problem. Charles Misner, Thorne, and John Wheeler had just rewritten the subject in an epic text known widely as the *Big Black Book*. Unfortunately, it was almost impossible to learn from, especially by me. It was intended to present the subject in a geometric way, which most people would take as a good thing, but it went too far, so that it seemed like reading pictures. Robert Wald, several years later, presented the geometric story in a more conventional way. For me, Weinberg's book, following particle physics as much as possible, was ideal, and I learned this way as a grad student. Weinberg explicitly downgraded the role of geometry in gravity, never even mentioning black holes.[4]

In field theory we had a notable guest lecture from David Politzer, a new member of the department. Three years earlier, David Gross and Frank Wilczek from Princeton, and Politzer from Harvard, had discovered the principle of asymptotic freedom. This showed that due to quantum loops, the interaction strength of the strong nuclear force could grow larger at larger distances.

This then explained how the weak force seen between quarks at high energy was consistent with quark confinement at long distances. Thus, they had determined the nature of the strong nuclear force, so-called QCD, and established QFT as the correct framework for particle physics.

Unfortunately, no one at Caltech had been working on this. Feynman and Gell-Mann each liked to follow their own directions, though ironically asymptotic freedom explained the relation between Feynman's partons and Gell-Mann's quarks. So Politzer was the first direct connection with the new physics.

Another source of particle physics excitement was the discovery of a new long-lived heavy particle, something that had not been seen before, the J/Ψ. This was big enough news that even the undergrads knew they should attend the colloquium. After the observation was described, various faculty members put forth their theories. Feynman thought it might be free quarks, while a young professor, Glennys Farrar, proposed that it was a bound state of the charmed quark with its antiquark. Fairly quickly, the latter was confirmed. In fact, the existence of the charmed quark, as well as its mass and other properties, had been correctly predicted by Sheldon Glashow, John Iliopoulos, and Luciano Maiani several years earlier, a great success of theory.

For nonspecialists, here is a handy list of acronyms:

AdS/CFT: equivalence between quantum gravity in a certain curved space and a supersymmetric gauge theory in one less dimension

AdS/CM: use of AdS/CFT to model strongly coupled condensed matter systems

AdS/QCD: use of AdS/CFT to model strongly interacting nuclear systems

BFSS: matrix theory. Exact description of M-theory

BHC: black hole complementarity

BPS: partially supersymmetric state

CGHS: a model of gravity in two dimensions

GR: general relativity. Gravity arising from the curvature of space and time

GUTs: grand unification theories

KKLT: first full model of stabilized string vacua

QCD: quantum chromodynamics. The theory of the strong nuclear force. The *chromo* comes from Gell-Mann's whimsical labeling of the three kinds of quark as red, green, and blue.

QED: quantum electrodynamics. The quantum theory of electromagnetism

QFT: quantum field theory. Quantum theory in which the basic variables are fields. Confirmed in 1971 as the basic framework of quantum mechanics and matter. The particles appear from the solutions for the quantum mechanics of the fields.

SUSY: supersymmetry

QUANTUM FIELD THEORY

Quantum field theory (QFT) is the framework in which everything in the universe is composed of *fields*. A field is an entity that permeates all of space and time, and assigns a mathematical value to every point in the universe. This notion was first introduced by Michael Faraday as an explanation of long-range electromagnetic effects, such as the deflection of a compass needle due to the magnetic field of a magnet.

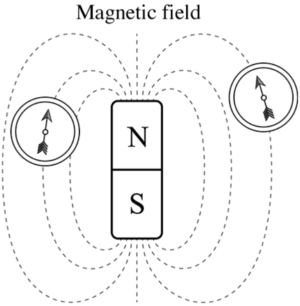


Figure 2.2a

What, then, are particles? That's where the *quantum* nature of a field comes in. In quantum mechanics, a field is *quantized* into discrete lumps of energy called *quanta*. These discrete jumps in the value of the field—the field excitations—are precisely what we call particles. Each type of field has its own associated particle, such as the electron of the electron field, photon of the electromagnetic field, and so on. In physics, these fields are represented mathematically as a quantum mechanical operator—namely, a map from the empty vacuum state to that of a single particle.

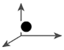
$$\Phi(x)|0\rangle =$$ 

Figure 2.2b

The first step in defining a QFT is to list all the different kinds of fields, each with its own individual properties such as the mass of the associated particle, along with the different ways the particles interact. This is packaged into its *Lagrangian*, or sometimes its *action*—the spacetime integral of the Lagrangian. The Lagrangian splits into a *propagator* that describes how the particles move, and a series of *interaction vertices* that describe how the particles interact.

$$L = \Phi(x)\left(\partial^2 + m^2\right)\Phi(x) + \overset{\substack{\text{Coupling strength}\\ \downarrow}}{\lambda}\Phi^4(x)$$

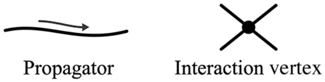


Figure 2.2c

Quantum theory is not deterministic, and therefore predictions come in the form of probabilities for a given set of events to occur. An important one in QFT is the *four-point function*, which measures the probability of two incoming particles to scatter into two outgoing ones. This probability is calculated diagrammatically using *Feynman diagrams*, the spacetime representation of all processes allowed by the rules laid out in the Lagrangian.

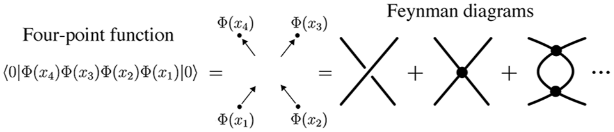


Figure 2.2d

GENERAL RELATIVITY

One of the most shocking discoveries in the twentieth century was that the force of gravity, the most ubiquitous force in the universe, is an illusion caused by the distortion of spacetime. According to Einstein's theory of general relativity (GR), the energy of a large massive object *bends* the spacetime around it causing smaller objects to "fall" inward.

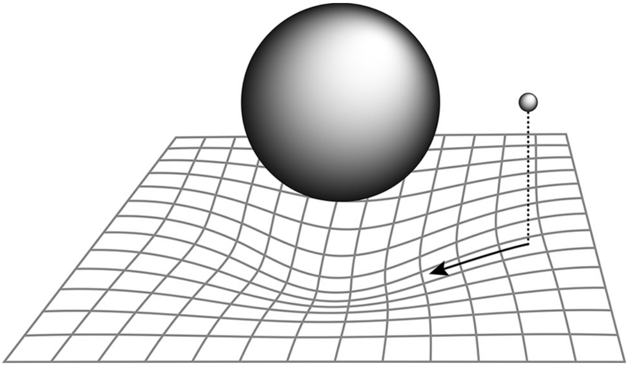
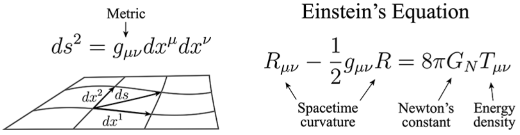


Figure 2.2e

All the information about the shape of spacetime can be packaged into a field known as the *metric*, which measures the distance between nearby points. The *curvature* of spacetime, a measure of its warping and hence the “force” of gravity, is determined by the metric. The interaction between spacetime and matter is governed by Einstein’s equation, relating the spacetime curvature to the energy density of matter. The strength of this interaction is controlled by Newton’s gravitational constant.



$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}$$

Figure 2.2f

In a quantum theory of gravity, the metric is promoted to a quantum field, giving rise to the *graviton*—the elementary particle of gravity. While quantum gravity requires more structure to be defined precisely, there is a *perturbative* approximation, when spacetime fluctuations are small, where it is described as a standard QFT interacting with matter. The Lagrangian of this theory makes it manifest how the gravitational force is mediated by graviton exchange.

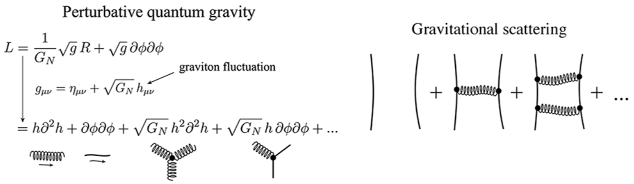


Figure 2.2g

Notes

1. Kip was awarded the 2017 Nobel Prize in physics “for decisive contributions to the LIGO detector and the observation of gravitational wave.”

2. In phase space, the Fourier transformation $x \to p \to -x$ is a 90° rotation. So rotate by 45° (or 225°, it’s nonunique).

3. Zajc reminds me of another interaction we had with him, asking about whether rotating bodies produce gravitational radiation, something we were puzzling over.

4. It occurs to me that even today, our most precise description of black holes is gauge theory, not geometry.