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Quarks,
Spacetime,
and the Big Bang

Michigan State University

Preface:

Quarks, Spacetime, and the Big Bang

QS&BB is a book designed to accompany a general education course of the same name that I've taught at Michigan State University for a number of years. Why? Well, there's a story there.

The North American approach to university education is nearly unique in the world. Citizen-students come to college in order to become proficient in a focused few areas of study (your "major") but are also broadly educated in many other areas ("general education"). So an English major would dive deeply into literature but also take courses in maybe physics, astronomy, chemistry, biology, geology, history, anthropology, psychology, etc. Likewise a physics major would study physics and mathematics, but also biology, literature, psychology, and so on. Every U.S. campus manages this deep-plus-broad approach to higher education its own way.[1]

Creating courses for non-specialists in the sciences is especially challenging, but important since many of society's big problems are scientific at their roots.[2] An informed citizen needs to understand some scientific facts, but also appreciate the scientific method as all too often, controversy swirls as much around what is or isn't "science" as it does to the details. How best to do this in physics?

There are many physics courses for non-science college students. The traditional course is often called "Physics for Poets," which is a conceptual (less mathematics) version of the otherwise full-physics curriculum taught to science and engineering students. But there are other paths which teach physics by shining a light on particularly interesting topics in accessible presentations.[3]

[1] This approach to higher education is credited to the Harvard University president Abbott Lawrence Lowell who began transforming undergraduate education in 1909. Under him, fields of concentration (majors) were established along with required sampling of courses outside of majors, the distribution requirement. "A well-educated man must know a little bit of everything and one thing well." affected college education across America to this day.

[2] Climate change. Energy production. Evolution and big bang in schools. Nuclear power. Nuclear proliferation. NASA. NIH. Vaccination. Pandemics. Weather. Health effects (or not) of common radiation sources. Peer review. Basic versus applied research. And so on.

[3] Many physics departments will offer astronomy courses (or of course, astronomy departments will when they exist), physics of music, physics of energy issues, physics of light, and so on. Our department is no different in that respect. By the way, 50,000 students take college-credit astronomy every year in the United States!

What QS&BB Isn't

This book is not a comprehensive survey of all of physics. A student will not be expected to solve many of the standard "physics class" problems—QS&BB is intentionally, mostly conceptual. Many topics which would be in a conventional course are not covered here, or touched on lightly. For example, there is no chapter on thermodynamics nor on energy production or climate. Motion and forces are only presented for one-dimensional situations and only sufficiently to appreciate relativity. Electricity and magnetism are covered in a descriptive way, with only a few quantitative examples. "How things work" is sometimes covered, but less so than from the usual survey course.

We cut a strategic path through "classical" areas of physics in order to accumulate the concepts, quantities, and vocabulary that would apply to a conceptual appreciation of relativity and quantum mechanics, both of which are the jumping-off points to our two main topics.

The level of scientific literacy among college-educated young adults in the United States always ranks among the top two or three among all nations of the world. This research has been done over decades by Professor Jon Miller of originally, Northwestern University and Michigan State University, and now the University of Michigan. In an article for the Association of American Colleges & Universities ("What Colleges and Universities Need to Do to Advance Civic Scientific Literacy and Preserve American Democracy" `https://www.aacu.org/node/2139`) he explains why U.S. results are so positive: "The answer is college science courses." He goes on to note that "The United States is the only country that requires all college students to take one or more science courses as a part of a general education requirement. In a series of statistical analyses using structural equation analyses of both cross-sectional and longitudinal data, I have shown that exposure to college science courses is a strong predictor of civic scientific literacy in young adults and in adults of all ages (Miller 2010a, 2010c)."

What QS&BB Is

My aim is to help you appreciate two of the more exciting "fundamental" topics in physics, particle physics and cosmology. You'll come to appreciate our current picture of how our universe began and what open questions continue to motivate thousands of us around the world. In order to get there we need a working knowledge of some of the classical subjects and these are presented in the early chapters in a gentle way. We start with a conventional, but abbreviated approach to the classical subjects of mechanics and electricity and magnetism with some simple algebra-based descriptions and examples in the early chapters. After about a third of the book, this light-mathematical approach evolves into a more conceptual narrative where we tackle modern-day topics. The Chapter 1 describes how the book—and the Michigan State course—are organized in more detail.

I emphasize biography. We'll meet intellectual giants whom everyone has heard of, but also our professional scientific heroes whose images are *not* on tee-shirts. The history of physics and astronomy is full of unusual people—and a lot of just plain folks—and I'm eager for you to think of us without white coats and strange manners. We're regular people who chose career paths that are a little outside of the mainstream. But we're not so special except that we are privileged to be supported by the public in order to do our work.

I'm an experimental particle physicist and I've been teaching physics to physics majors and especially non-science students for more than three decades—I hope well. I know I have fun doing it. I'm lucky enough to be continuously supported by the you[4] for my research in Particle Physics for three decades

[4] The National Science Foundation, specifically.

and I'm grateful. In some ways, this book and course are in partial repayment for that support.

I like knowing how the universe works and I've never met anyone who didn't share my curiosity. Even after a lifetime daily immersed in these matters, I'm constantly in awe at how beautiful it all is and how lucky we are to know as much as we do. I enjoy talking about it and teaching some of the details.

Figure 1: You can find more about me at http://www.pa.msu.edu/~brock/. You'll get to know me as I tell you stories in the pages that follow. Unfortunately, I'll not be able to meet you!

I'm not stuffy. I've tried to write here like I teach, which is informally and hopefully without pretense. I'm deadly serious about the science and passionate about the subject-matter. But I also like to have fun and hopefully I'll make you smile every once in a while and help you to grasp complex ideas. Stay with me, and you'll be able to explain Special Relativity at parties just like I can![5]

[5] Wait. That's not necessarily a selling point.

Chapter 1

Introduction

Studying the Smallest and the Largest

The Large Hadron Collider, looking south across Lake Geneva and the Swiss Alps

"In the beginning, the universe was created.
This has made a lot of people very angry and been widely regarded as a bad move." *Douglas Adams*

We're about to follow a Big Story —the "just so" story of the beginning of the universe. Yes, that one: Everything. The plot of this story seems to have all sorts of twists and turns that we're still unraveling. Surprises await.

Of course, the details are where the devil resides and they are fiercely complex. So much so that two entirely different scientific communities are deployed to battle with nature: those of us who work on the "outside" and those who explore the "inside." The outside crew are astronomers and astrophysicists. They measure and characterize the constituents and nature of the cosmos. They look *out*. The inside teams mimic the earliest picoseconds of the universe by recreating its incredibly hot, adolescent conditions in laboratories here on the Earth. These are the particle physicists and they look *in*. This is the story of both.

What's the smallest real thing that you can know about? For people of my *grandparents' generation*, the sophisticated answer would be "what you can see." I was born in the year 1950, and so my grandparents would have been children about 1900 which is when physics got interesting. They would have been taught that to claim existence for an object that the naked eye could not see would be to utter an absurdity. Chemists spoke of atoms, but were disdainful of anyone who thought they were real. They were just a shorthand picture for how to visualize elements. Physicists were even less flexible.

"Quarks"? "Leptons"? Lots of jargon and I'll keep it all straight for you as we go along. For now, quarks are itsy-bitsy pieces of the proton and leptons include the electron and others.

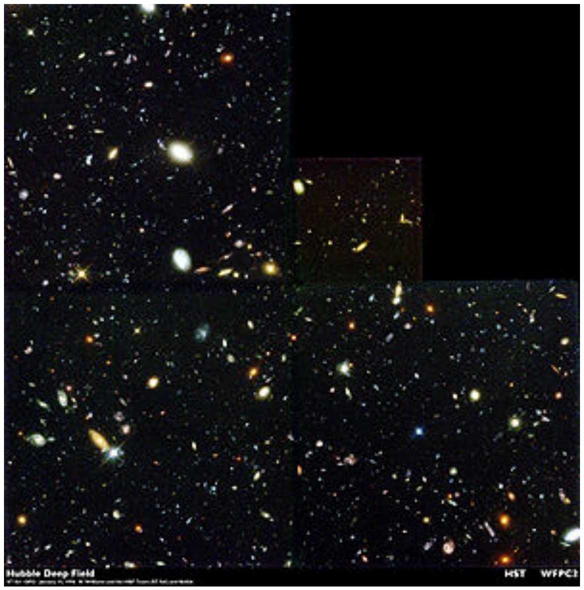

Figure 1.1: The so-called "Hubble Deep Field" view of a tiny spot in the sky, filled with 3,000 galaxies.

For people of my *parents' generation*, the answer would have been "protons, neutrons, and electrons." The atom had been thrust into believability around the turn of the century, and then refined during the next two decades. But the neat planet-like picture of the atom was where it all stopped for many.

In *our generation*, the answer to the "smallest" question has been "quarks and leptons" ...but with the full expectation that they may not be the end of the "smallest" story. We approach this question differently now. We're hard at work, as "we speak" using brand new tools to explore further than ever before.

In *your generation*? The sky's the limit! We've hints at solving some old puzzles and we'll undoubtedly find new ones. We're developing and deploying amazing new instruments and theoretical ideas now rub shoulders with not just nature, but philosophy and the deepest questions asked by humans. Your generation is going to see amazing things.

Through decades of intense experimentation and imaginative theorizing, the tiniest bits of reality are turning out to be a fascinating collection of objects. In the 1950s and 1960s, we just stood back and tried to catch the hundreds of particles that our experiments spit out at us. New particles every year! Names that nobody could remember. Hundreds of them, which was ludicrous! Didn't nature have some plan?

Well we uncovered a plan that we think is a very good picture of how much of the fundamental particles of the universe work together and we've been exploring it since the 1970s. We've knitted that earlier mess together into a coherent picture of the entities themselves as well as the rules that govern how that stuff behaves.

But we're unhappy. Our grand synthesis of the Tiniest Bits Story—called the Standard Model — now looks a little shakey. While its been the gold-standard of the successful scientific theory, we expect that *new* tiny bits are lurking in our experiments and we will be astonished if nothing shows up as we dig deeper.[1] This new anticipation would have been met with blank stares only a couple of decades ago.

So much for inside effort.[2]

[1] These new states of matter might be: "additional quarks, the Higgs Boson, Supersymmetric Particles, Weakly Interacting Massive Particles (WIMPs), Dark Matter particles. . . ," all famous candidates for future discovery. Of course whenever we get too cocky, nature plots to surprise us with something completely unexpected—more often than we'd like to admit! So, we're instinctively wary of being too sure of what's coming.

[2] See the frontispiece of this chapter!

Okay. So what's the biggest real thing you can know about? For people of my *grandparents' generation* the learned answer to this question would be "the size of the Milky Way," which they would have been taught constituted the whole universe. Everything visible in the night sky was thought to be a part of one big, but still cozy cluster of stars which we see to be densest around the southern sky (from North America). Not only was my grandparents' universe compact, it was supposed to be permanent—static and unchanging— built of three kinds of objects: planets, stars, and clusters of stars. Stars twinkled, planets were steadfastly bright, and clusters of stars were fuzzy, indicative of their presumed distances from us. Sure, they all moved with regularity during each night and shifted slightly in a year, but the large scale structure of my grandparents' universe was simple: a nice, intimate, dependable universe.

For people of my *parents' generation*, the universe suddenly become huge. Those fuzzy clusters were found to be other galaxies outside of the Milky Way which are surprisingly far from us—we're not alone in our comfy galaxy. They were taught about thousands—we now know, billions—of others, of which the Milky Way is a relatively modest and ordinary example. But, the real shocker was the overthrow of the static universe of my grandparents. My parents' universe was found to be flying apart—expanding—at a breakneck speed. No longer a tight-knit, stable thing...the universe is now huge and reckless.

The really unsettling piece of news for *my generation* is that the Big Questions of antiquity are now legitimate scientific research programs: Was there a beginning to the universe?[3] Are we alone? Will the universe end? Are there other universes? Was there anything *before* The Beginning? What drives the expansion of our universe to accelerate? The outside crowd thinks big thoughts now and this is a development of only the last couple of decades.

[3] There was a battle royal between two competing models of the universe in the 1950s. The first was dubbed by a proponent of the second, the "big bang"—not as a compliment. The second model was called the "Steady State" model. We'll talk more about these later. This battle raged until I was in high school.

When I was in graduate school, a professor told me that Cosmology was "physics knitting." Not any more! Cosmology in my and especially *your generation* is going to be flat-out amazing!

1.1 An Auspicious Beginning

Yes. The observable universe had a beginning and quite a beginning it must have been: a roiling mess of radiation and elementary particles at temperatures never to be seen again. Everything that is would have been confined into a size smaller than the smallest particle we know of.[4] Unimaginatively dense and with growth that was stunningly rapid, our early universe defies imagination. It's so outrageous that comprehending it seems a job for fiction and not science, yet my generation has also found ways to explore it: we probe it through direct telescope observations and we remake it in particle collisions. This is the blending of the outside with the inside pictures that motivates me.

[4] Maybe. Maybe not.

Wait. *I don't believe in the big bang. You appear to, but Isn't what you think just another "belief"? Aren't we each entitled to our own beliefs?*

Glad you asked. *"Believe" is a tricky word that we all use, although in our context, we should be clear. When I say "I believe in X," treat that as shorthand for the sentence: "X is highly confirmed by experiments and X likely to survive any future experimental test." If I'm an expert in the field of X, then I have the obligation to describe those experimental tests. If I'm not an expert in X, I should expect that an expert could also enumerate its experimental successes in detail. There are do's and don't's about this in science. About scientific belief, I can't do three things: 1) I can't say that I believe in X because I want to, 2) I can't say that I believe in X because my gut or a "feeling" tells me to, and 3) I can't say that I believe in X because a non-expert or an ancient text tells me to. Likewise, I can't say that I don't believe in X for any of those same three reasons. Stay with me. What I'll show you are amazing things and a record of success that's hard to ignore. Science is a process as well as a collection of theories!*

Quarks, Spacetime, and the Big Bang (which I'll affectionately refer to as "QS&BB") tells the interleaved stories of the two sciences of Particle Physics and Cosmology and how they have come to be blended together into a believable picture of how we all came to be. We're deep into the narrative—the plot is well understood, the characters are developed, and a "can't put it down" fever has set in. We're eager to see how it comes out and we're doing experiments all around the globe—and in orbit *above* the globe and in deep underground laboratories *inside* the globe— to push ourselves to the story's climax.

Definition: Particle Physics.
The study of the smallest bits of energy, matter, and the rules that govern their interactions.

1.2 The Inside Game: Particles and Forces

Sure, we've learned a lot in the last four decades about the Particle side of this story—my whole professional life. But, what's particularly interesting about this coming decade in EPP is that we've reached an impasse. We have bushel baskets full of theories about what should come next, but we're starved for new data which will direct us on how to sort out the various theories. You and I are going to explore that situation because new data are coming in right now at extraordinary international laboratories. The coming decade is going to be interesting.

Definition: Cosmology.
The study of history and the future of the whole universe.

The inside story is that of "Elementary Particle Physics," (aka "EPP") or as it's often called, just "Particle Physics," while the outside story is that of "Cosmology." We'll travel these narratives sequentially from their common beginnings.

The Particle Physics side is a well-established field practiced by about 10,000 of us in nearly every country and with major labs on four continents: North America, Europe, Asia, and Antarctica.[5] We build accelerators to provide beams of electrons or protons and crash them together. We then collect the debris from those collisions in gigantic "detectors" that allow us to unravel the products of those collisions.[6] Or we build detectors that are exposed to cosmic particles. EPP is one of many sub-disciplines in physics, but it's a little different. The questions of most of science have evolved in time as people became smarter and new problems became interesting. New disciplines sprang up as things got more complicated and challenging.[7] In contrast, while Particle Physics has become specialized and sophisticated, its goals have always been intensely focused on two questions:

[5] Isn't Antarctica a continent? Yup. Lots of experiments at the South Pole.

[6] Chapters **??**, **??**, and **??**.

[7] For example, Nuclear Physics and Particle Physics were practiced by the same people until the 1950s when they naturally split into two different subfields of physics. One group pursued the intricacies of more and more complex nuclei and the other pursued the complexities of the simplest objects. Each approach requires specialized devices and each separate theoretical tools.

What are the most elementary particles in nature? *Key Question 1*

What fundamental forces act among those elementary particles? *Key Question 2*

We think that getting closer and closer to answering these two questions will lead us to a deep understanding of the early universe. Paradoxically: understanding the tiniest things in nature will help to understand our "origins" which have been debated and argued for 2500 years.

Box 1.1 A little philosophy

By the way, do you see how these two key questions are different? The first one asks about the existence of "things." An inventory. The second question asks about physical laws *among* the things. We're realists, which is to say, we think that things are real and that our theories are about real processes. While these two ideas are debated in philosophy, scientific realists would refer to these two questions as "entity realism" and "theory realism." The former is more easily defended than the latter. But, we're not philosophers. We're scientists and we believe that the discovered laws of nature are factual statements about how things work. Enough of this.

These first two questions were stated carefully, so let's take them apart: "elementary," "particles," and "forces" are all three specific ideas in my world that have different meanings from normal peoples' worlds! How about parts?

1.2.1 What's "Elementary"?

The most basic qualification for some entity of nature to be "elementary" is: no parts. Most things have parts: stars, trees, molecules. Even an atom has parts—the nucleus, which can be multiple protons and neutrons, and the atomic electrons all constitute "parts." So, an atom is not elementary and not a subject of our investigations in particle physics. Every nucleus has parts and those parts—the proton and neutron—have parts![8] The electron? No parts. It's elementary.[9]

[8] Chapter 23

[9] So far.

An elementary particle is a bit of matter and energy that has no constituent parts. *Key Concept 1*

"Elementary ≡ no parts" is a simple idea.[10] But, as you'll see if there was ever a pattern in 20th century physics, it's that thinking hard about simple ideas quickly leads to the weird. A part of the theme of this book is to emphasize how simple ideas about nature can become wonderfully complex.

[10] The symbol ≡ means "defined as" or "equivalent to."

"Here's your moment of zen": "Simple means complex"!

1.2.2 Why "Particles"?

Here's one story: It appears that nature "clumps" energy in particular ways. If somehow we could prepare a bundle of energy—say, really-really hot, radiant energy—it will appear to condense quickly into very specific objects which go by various names: the fancy designation would be "quanta." But, what is left over after such an energy-bundle settles down are the "particles" we know and love: electrons, protons, and neutrons...and the other sets of particles that are relatively new: quarks, leptons, hadrons, bosons, and presumably those that we've not yet found. Nature makes only these particular states, some of which are produced readily, some rarely. Why? What governs how this happens?[11] Further, we get only whole electrons, not half electrons. Why?[12]

[11] We don't know!

[12] We don't know!

> Before Maxwell, Physical Reality ...was thought of as consisting in material particles.... Since Maxwell's time, Physical Reality has been thought of as represented by continuous fields, ...and not capable of any mechanical interpretation. This change in the conception of Reality is the most profound and the most fruitful that physics has experienced since the time of Newton. Albert Einstein, in "Maxwell's influence on the development of the conception of physical reality," in *James Clerk Maxwell: A Commemorative Volume* 1831-1931, (The Macmillan Company, New York, 1931), pp. 66-73.

But, things are not quite as simple as that first story of everything as particles. There's another story, and it's actually closer to the truth. As we'll get a taste of later, when we combine the theory of quantum mechanics with the theory of relativity, we find that the basic "stuff" that eventually arranges itself into atoms, people, and stars is actually a set of continuous *fields*.[13] Now that's disturbing since a field is everywhere, but a particle is "there." So there's the appearance of a conceptual contradiction and physicists have been working it out for more than 80 years. Notice, I didn't say that there's a logical contradiction in quantum mechanics. It's the most accurate description of nature ever devised! No, the problem is ours: this "conceptual contradiction" is one that exists between our ears as we try to translate our mathematics into pictures that we can keep in our heads and yes, write in words.[14]

[13] Chapters 13 and **??**

[14] Chapters **??**, **??**, and **??**

I have to admit to the mental crutch of *particles*. Even though the mathematics seems to require that all states of matter have both wave-like and particle-like properties for EPP it's easiest to mostly use the mathematical language of particles and that language came to us from Richard Feynman.[15]

[15] Chapters 6.5, 19, 21, 22, and 25

So, one side of my brain is full of the sophisticated symbols and manipulations of the relativistic quantum field theory that precisely describes this stuff. But the other side of my head is full of images of billiard balls bouncing off of one another: colliding particles. It's not an entirely satisfying picture since in order for this analogy to be precise, my mental quantum billiard balls should also randomly decay into other billiard balls—or into baseballs or bananas,— should pass right through other billiard balls, and even spontaneously leave my pool table and appear on someone else's! But, we have to cling to some picture in our heads and that's mine.

1.2.3 What "Fundamental Forces"?

"Force" is one of those words that has many colloquial meanings.[16] But in physics a force is a precise concept—a noun and not just a verb. Here's the simplest notion of a force: if you've changed the motion of an object, you had to exert a force in order to do so.

Definition: Force.
Anything that alters the state of motion of an object is a force.

[16] "May the Force be with you."
"You can't force me to eat that!"

Everyday Forces

You and I deal with three kinds of forces every day. Let's talk a little about all three...and then how the forces in Particle Physics are different from these.

First take regular pushing on something—whether it's a push that's through muscles against something, or the push of a tire (or your shoe) against the road—seems to be a separate force of its own. You have this mental picture that when you touch an object and push that this mechanical thing-to-thing contact is the cause of the object's change of motion. You might be satisfied with the phrase "mechanical force" as all you need to say and you'd be consistent with its modern usage in engineering. File that away for a moment as a particular kind of force.

But what about a magnet? Surely at one point in your young life, you've played with a pair of magnets and marveled at the fact that they seem to "communicate" with one another. Without touching, and without any obvious connection between them, a force is transmitted through thin air. Here's another one that doesn't need direct contact: your hair's state of motion is affected on a cold, dry day by a comb—your 'do rearranges itself as if by magic without touching the apparent cause of the hair motion—a statically charged comb.

One of the neat stories we'll uncover is that the relationship between your hair's unruliness in January and the dog's picture sticking to your refrigerator is an intimate one: they are both examples of a single force, the "electromagnetic force" and understanding that will take us into Albert Einstein's young life.[17]

[17] Chapters 13, ??, and 15

The electromagnetic force is blind to anything but the amount of electric charge. If we place a charge of $+Q$ on two ants, they will be repelled by that electrostatic force between them. If we place a charge of $+Q$ on two elephants they too will be repelled...by exactly the same electrostatic force. Electricity "sees" only electric charge.

Shh. Now, a well-kept secret: the mechanical thing-on-thing pushes and pulls of everyday life are actually electromagnetic: the reason your hand doesn't go right through the box you're pushing is because the electrons in your hand are repelled by the electrons in the surface atoms of the box and so you. . . push it.[18]

[18] The reason you don't pass right through the floor is due to the same electrostatic force.

So the idea of a force in EPP is not what you obviously experience in everyday life. Nature's fundamental forces are very precise and very selective pushes and pulls that exist among particles. "Precise" because there is no wiggle-room. The force between two electrons some distance apart is precisely the same as the force between any two electrons with that separation. "Selective" because that same force would exist between two protons of that separation, but be zero if the electron or proton is replaced by a neutron. The electric force only acts on particles with the attribute of electric charge. And finally, the forces are all of different strengths. Your dog's picture stays on the refrigerator and doesn't fall to the floor because the force of gravity is very much weaker than the force of electromagnetism.

Definition: Electromagnetic.
The theories of electricity and magnetism were shown in the 19th century to be actually a part of a more fundamental theory which has come to be called "electromagnetism." The forces, both electric and magnetic, are called the Electromagnetic Force.

1.2.4 Particles, Forces, and Theories

Just enumerating particles is like physics-stamp-collecting. But if there was a confirmed theory that linked the forces and the particles into *a single, deductive story*? Well, that would suggest that we'd learned something important about nature.[19] One of the amazing accomplishments of the last three decades in particle physics is that we do have a particular theory, called colloquially "the standard model" that explained how the forces originated and predicted the existence of particles which were eventually discovered.

[19] Chapter 30

How Many Forces Are There?

How many forces nature knows about (we just talked about two fundamental forces: electromagnetism and gravity) and how they act on different constituents is for us to figure out. Unlike the everyday mechanical force, where I can push on a wooden box as easily as I can push on a lawnmower, fundamental forces are related to rather specific qualities of particles. The electrostatic force only "sees" electric charge, the gravitational force only recognizes mass: anything that has a mass feels an attractive force to all other massive things. It doesn't matter what color it is. It doesn't matter what material the two objects are made of, it also doesn't matter what their electric charge is, if they have mass, then the gravitational force is going to act... and do so by attracting them together.[20]

[20] No gravitational repulsion here...or is there? Stay tuned.

Now, the story is a little more complicated than this introduction. For the record, just to be complete, it's not only mass, but also energy that is affected by the gravitational force. And, we've some reason to think that traditional gravity may even have a repulsive component to it on cosmological scales! Finally, the gravitational force is the only one that resists an explanation using quantum theory, and so it holds some really well-kept secrets that we would very much like to uncover.

Nature is pretty economical. If there are 12 kinds of particles in the universe, you might guess that maybe there's one force, or 6 or 12. But, it turns out that there appear to be only 4. We've encountered two of them: gravity and electromagnetism. But, by experimenting for nearly 100 years, we've found that there are two more forces. And, like electricity and gravity, these forces also pick out particles with particular attributes and ignore the others. Some particles respond to just one force. Some of them respond to two or three. We want to understand this. Badly.

Besides electromagnetism and gravity, the other two forces are called, get ready: the Weak Force and the Strong Force. They are, as you might guess, weaker and stronger than some others.[21] We'll talk a lot more about these later, but from weakest to strongest, the forces order themselves:

[21] We have a lot of fun naming things in particle physics.

1. the Gravitational Force,
2. the Weak Force,
3. the Electromagnetic Force, and
4. the Strong Force.

So, in reality, the only two forces that we experience in everyday life are electromagnetism and gravity. The others act behind the scenes.

1.2.5 Particle Confusions

Our standard model now has no missing pieces. It's a complete description of just about everything that we've ever manipulated on Earth! This result was sealed in 2012 with the announcement that we had found a strange particle called the "Higgs Boson" in our experiments at the Large Hadron Collider at CERN. But we're not happy. And we're not happy for two reasons. First, there are experimental reasons: something's going on in the universe that causes galaxies to move oddly (see below) and something's going on with nothing. That is, with the vacuum, which we tend to think of as related to that theory of fields that I described above. The second reason that we're not happy is that the standard model has some formal features about it that don't quite sit right with us. We need to do an odd thing in the mathematics to get it to work and we're pretty sure that this "odd thing" should have a formal basis and not be quite as *ad-hoc* as it seems.[22]Let's go large.

[22] Want to know what that odd thing is? We take an equation, and we change the sign of one term from negative to positive. No particular reason. . . except that it works. Stay tuned, you'll see.

1.3 The Outside Game: The Big Bang

As I've indicated the big news of the 20th century is that our cosmos appears to have had a beginning. Astrophysicists have made huge strides in the last three decades with amazing instruments on Earth and in orbit. Once the big bang was hinted at in the late 1960's, satellite observatories have sealed the deal. Our universe had a beginning.

Definition: Astrophysics.
The study of the dynamics and the origins of astronomical objects.

Stand back and think about the implications: this is the most remarkable scientific discovery in history. Of all of the ways people have thought about their place in the world, over thousands of years there was only speculation and myth about a possible Beginning. After decades of patient research, we know: there was a time—before which there was nothing. Suddenly, in the blink of an instant space, time, and the energy of matter and radiation were born and the subsequent cooling eventually caused our universe to evolve. Into us.

Cosmology is an old, old metaphysical or religious subject (habit?), but it only became a *science* in the last century. Traditionally, Cosmology is the story of the whole of the universe. From the creation stories to the "just-so fables," humankind used mythology and belief to orient themselves with the universe they could see. There was the strong sense that the whole of the universe was bigger than what humans could imagine.

Some would call this later version, Physical Cosmology in order to distinguish it from the precursor story-telling. (I'm looking at you, Wikipedia.) But we'll just call it plain, old Cosmology.

Well, we don't "imagine" any more. We measure. Cosmology is a new science and it became one in the hands of Albert Einstein in the early twentieth century. Things didn't quite go as he'd planned, as we'll see. But he laid the groundwork for a human-based study of the universe using mathematical rules rather than mythology or belief. Today it's among the most exciting branches of all of physics.

The two basic questions that modern cosmology tries to understand the answers to are these:

What are the past and future histories of the universe? *Key Question 3*

What are the ingredients of the universe? *Key Question 4*

These questions area alsoo carefully stated. So let's unpack "universe," "history," and "ingredients."

1.3.1 Histories of the Universe?

You know the meaning of "Universe," right? It's...well...it's everything. At least that's what it used to mean. We'll consider a growing suspicion is that a *universe* might be a relatively local object and that there might be room for an interpretation of the whole cosmos that could incorporate other *universes*.[23]

[23] Now, did you ever think that there could be a plural of that word?

Perhaps you've read that there is consideration of a "multiverse" in which there are an infinite number of universes which are born and die spontaneously and for eternity. All of them would have different physical laws and so different particles and varying potential for life. To some, still unconfirmed mathematical models push to this conclusion. To others, this is speculation that's beyond wild.[24] We'll talk about why the multiverse is a topic for science seminars and not just comic books. On this, we'll be agnostic. Just the facts, ma'am.

[24] For some, even reckless and unscientific.

But in order to be specific, we should try to define what our universe would entail. Our universe is

1. the one in which we (or our original elements) reside,
2. the one where the same physical laws work throughout, and
3. the one that had the big bang that our evidence points to..[25]

[25] It ain't much, but it's home.

Certainly, the past history of the universe is the hot[26] topic in all of cosmology.

[26] No pun intended.

Past History

Our inference to the need for a beginning—a big bang—comes from a) the fact that the universe is expanding, b) that we therefore infer that it was smaller in the past, and importantly, c) that we have a plausible, predictive model that describes this situation. Both the fact of the big bang and the stories that led us to this conclusion are fascinating and we'll spend quite a bit of time unraveling them.[27] But just how this happened is a matter of urgent research.

[27] Chapters **??**, 27, and 29

We can play the universe-movie-camera backwards in our models and know where "the beginning" should be in time. The original "$t = 0$," nominally called the big bang. In the conventional model of cosmology we can reliably predict[28] the times at which atoms were formed, then when nuclei would have formed, and then even when protons and neutrons would have been formed. At that point the universe would have been unbelievably hot and dense and only consisted of the most elementary of particles. This birthday of matter is about a picosecond after the big bang: when the universe was about

[28] post-dict?

0.000000000001 seconds old.

[29] Chapter 30

Let's call this the "Electroweak time," which we'll study later.[29]

But as tiny as the Electroweak time is, it's still not zero. If we keep pushing our models earlier, we reach a point where our mathematics fails us with infinities. This is at called the "Planck time" and is at 10^{-43} seconds, or...dare I write it?...it's at

0.0000000000000000000000000000000000000000001 seconds.

This is a defining point. Before the Planck time, the very concept of "time" would not exist.

Anyway, between the Electroweak time and the Planck time a lot of physics had to have happened. We've models of what events to insert in that interval and tests we can perform to lend credence to them. [30] So the good news is that from the Electroweak time forward until now, we can explain how just about everything evolved. The bad news is that before that point, we come up against the 800 pound gorilla-question: **what "banged"?** The idea of an explosion of the loud-noise sort is not correct. So the past history of the universe is an active area of research, world-wide. Theory and experiment, in astrophysics and particle physics all work together on this.

[30] To complicate matters, space and time are intimately involved in this event in ways that we can't yet rigorously pin down.

Now put on your seatbelt. Could there have been a "before the big bang"? The general consensus is "yes" and the front-runner model—what some have called "an amendment to the big bang"—is called **Inflation**. This 30 year old idea predicts that at about 10^{-35} seconds the universe went through a phase transition, not unlike when water boils. Before that point, there was only the vacuum...a bubble of nothing. After the inflationary event, radiation and particles were created and our universe evolved until today.

This going from *nothing* to *something*—dubbed the "ultimate free lunch" by inflation's inventor—is heady stuff. But it's testable stuff. And it's bizarre stuff since inflation is part of the inspiration for the far-out notion that ours is only one of a "multiverse." This hypothesized infinite collection of other vacuum bubbles would be eternal (time wouldn't exist) and would be spawning other universes for all eternity. Some might become full-fledged universes with particle and laws amenable to making stars, galaxies, and carbon-based life. Some might not.

Future History

So with that out of the way, what is a future history? Well, I'm playing a word-game with you since we'll see that in physics the direction of time becomes a different sort of thing than what we're used to. But the eventual fate of the universe has been a matter of mathematical modeling since the 1960s. The universe could logically expand forever; stop, shrink, and collapse; or slow down and become static. Nobody was prepared for the surprise of 1999.

The results of independent measurements of a particular type of supernovae and their speeds and distances led to the conclusion that not only is the universe expanding, but that expansion appears to be *accelerating*. Something seems to be pushing space to stretch faster and faster and we're not sure what it is (but Inflation can accommodate it). Taken at face-value, the future seems grim for this universe. At some point the expansion will be so fast that light would not be quick enough to be able to travel from one galaxy or star to another. Every celestial object will become isolated. Anyone left alive on any planet in this universe would see only... **black**. It will be a lonely place.

Another future history comes from a model from physicists at Princeton in which after the universe's novel birth and then big bang-ish evolution it would actually experience a contraction of space, all the way to an eventual collapse ("Big Crunch"). And then the whole process would start over: the universe would be cyclic. An endless repetition of groundhog day cosmic repeats. In this scenario there is no unique beginning, but rather an endless series of beginnings.[31]

So you can see that while the knowing the past and future of the universe are age-old quests their unraveling might be puzzles that humans can actually solve. Our two most compelling models are physically different and even *philosophically different*! Inflation assumes that time had a beginning, while in the cyclic picture time is perpetual—never starts and never ends. Appreciating the details of these and other advances are a part of the QS&BB mission.

Time to lie down for a bit and let this sink in.

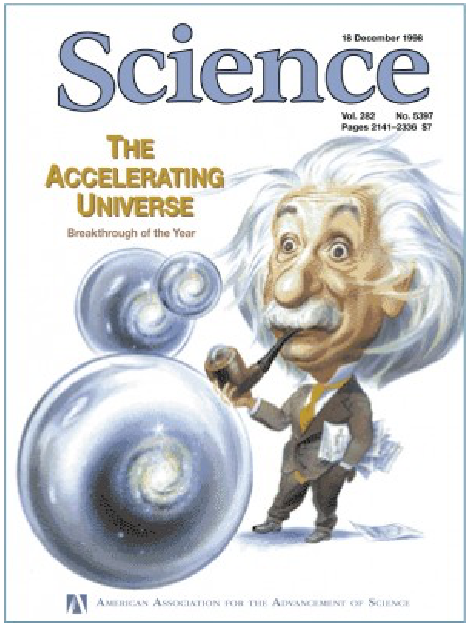

Figure 1.2: sciencemag

[31] This model is also consistent with the accelerating universe, but ascribes the cause differently from inflation.

1.3.2 Ingredients?

In order to inventory the ingredients of your world, you just look around you. Houses, clouds, Earth, the Moon, the Sun, stars, and so on. But the ingredients that I'm speaking of are courser-grained. First, the universe is incredibly big—and we'll get a sense of that—but the average amount of actual stuff is actually quite small, not much more than about 3 protons per cubic meter overall. So the overall density of the universe is minuscule, pretty smooth, and pretty much dominated by hydrogen atoms. So ingredient number one? The simplest element of all. All of interstellar and intergalactic hydrogen was born out of the big bang. All of the other elements[32] are made in stars.

[32] except for tiny traces of helium and lithium

An inventory of the other ingredients depends on the epoch in which we make the list. During our current era, we'll care about galaxies, a few spectacularly destructive stars (supernovae), and some stellar and galactic black holes. The atomic hydrogen and these shining objects are what we can apparently study directly since they all emit radiation. Thirteen billion years ago, we couldn't have included galaxies and thirteen and a half billion years ago, there would have only been particles and radiation. So understanding the evolution of the ingredients of the universe is a major undertaking, backed up with very sophisticated computer modeling and very precise satellite observatories.

In addition to the regular stuff of which stars are made, there are other ingredients which are more exotic. There is the radiant energy all around us left over from about 300,000 years after the big bang, and this Cosmic Microwave Background is now the object of many precise space missions.

Even more strange is whatever it is that dominates the motions of galaxies. They don't rotate the way we expect, given the otherwise reliable laws of gravitation. No, their motions suggest that they're (we're!) surrounded by unseen (not shining) stuff that gravitates but doesn't radiate: Dark Matter is our intriguing name for this stuff. There's room for Dark Energy in both the Inflation and cyclic cosmologies.

Finally, the most fascinating ingredient of the universe seems to be nothing. That is, the unseen force that seems to be pushing everything into that newly discovered accelerated expansion, might be a feature of the vacuum.[33] When we don't know what something is, we name it! "Dark Energy" is the placeholder name for the mysterious "something" that also is a target of frantic experiments and theoretical work.

Figure 1.3: vacuum

[33] We'll talk a lot about the vacuum, which until this discovery was the province of particle physics. Now both cosmology and particle physics intellectually own nothing!

1.3.3 Cosmological Confusions

In Cosmology we face some flat-out observational or *experimental* embarrassments. For example, when we add up all of the mass-energy of all of the objects that we can see using all of our observational tools (optical telescopes, infrared telescopes, microwave satellite telescopes, radio telescopes, etc.), 95% of the mass of the universe is missing. No kidding.

A part of the missing stuff appears to be that Dark Matter (about 30%) and the rest seems to be made up of Dark Energy. When you take the paltry 5% of shining stuff and add in these two "Dark" ingredients, it actually works out to 100%! This is a major victory for the "standard model of cosmology" or the "hot big bang model" (two names) and getting there is a part of the QS&BB story.

But we're confused about what Dark Matter and Dark Energy actually are. Embarrassed even. So there are major programs all over the Earth to study them.

Want stranger? Where are the antimatter galaxies? We don't see any evidence of relic antimatter in the universe. Only matter—the stuff we're made of. So either the universe began with an artificially enhanced matter dominance—an "initial condition" that is not scientifically acceptable—or at some point the originally *symmetric* matter-antimatter soup became our *antisymmetric*, matter-dominant outcome.

It gets still stranger. If you look at the sky to the West and do a careful analysis of the distribution of matter and temperature and then do the same thing to a part of the sky in the East, you will find that they are identical to a tiny fraction of a percent. The problem with that is that in the evolution of the universe, there is no way that the two opposite sides of the cosmos could have been in communication with one another.[34] By that, I mean that in order for these two patches of sky to be so precisely identical, they must have been in contact with one another in the past. The hot big bang model doesn't allow that.[35] They would have always been so far apart that even mixing propagated at the speed of light, the conditions of one part could not reach the other. Yet something connected them, but what? Let's play together.

[34] This is called the Horizon Problem among aficionados. Namely: *you* by the time we're done.

[35] while Inflation encourages that!

1.4 Particle Physics and Cosmology, Together

After 50 years of successes and surprises in both fields, one thing is clear: the reality of a big bang means that there was a period when the universe consisted of only particles and forces. No protons, atoms, stars, galaxies, or Starbucks. Just elementary particles and the forces among them.

That epoch was less than 0.000001 seconds long, but critical since the particles and forces were created just before it and what happened after was determined *by* the ingredients and rules of that period. What's more, we suspect that the set of forces *then* was different from those we know of *now* and that the set of primordial elementary particles might have included whole species that we've not yet found in terrestrial experiments.[36]

[36] As a tantalizing tease each of the cosmological problems above has candidate particle physics solutions!

These eras are not connected by a single story thread—yet. But they must be! So we have a lofty goal: we're working toward a model of *everything* about the universe from the big bang through to today. Theories abound, but experiment will decide. We can explore the earliest moments of the universe with the most powerful telescopes, but in order to investigate the times earlier than about 3 minutes after that Beginning, we need to do experiments in laboratories on our Earth. It's a bold extrapolation: by colliding protons head-on at very high energies, we're reproducing that early hot cosmic cauldron.

> **Wait.** *How do you know that this is the right connection to make? Maybe the conditions in the big bang were totally different than those in proton collisions?*
>
> **Glad you asked.** *It's a plausible story, and, frankly a nice one. But as pleasing as it is, we have to test it and what's neat about the state of affairs right now is that particle physicists are joining astrophysics collaborations and astrophysical measurements are directly testable in our labs on Earth. It could be wrong! But we have to pursue it with a vengeance since the stakes are so high.*

We're currently mounting experiments in both EPP and Cosmology that are going to hit these issues squarely in the next couple of decades. Their results will completely change the way we think. Textbooks will be rewritten. If the first 40 years of the twentieth century were wacky, the first couple of decades of the twenty first are likely to be amazing.

In my professional lifetime, these two fields have become kin. Theoretical and experimental advances (or surprises) in one field directly affect the other and visa versa.

The stakes are so high, that we can add a third focus for EPP:

How did elementary particles and their forces affect the evolution of the universe? *Key Question 5*

Like the ancient Ouroboros, the snake eating its own tail. Cosmology—the science of the biggest— is dependent on the science of the smallest, particle physics, and *visa versa*. That's our story: Elementary Particle Physics and Cosmology are now united in a single path of discovery and this book will show you how.

Figure 1.4: Ouroboros

QS&BB is not old "dead white guy physics"! It's all new and the details are still being worked out so we're going to be talking about matters of very current interest. If you make it through with me, you'll be in a good position to appreciate the surprises when they start to occur at the Large Hadron Collider, Fermilab's LBNF and DUNE, Mu2e, g-2, numerous underground laboratories, as well as the Planck Explorer, James Webb Telescope, the Fermi Gamma-ray Space Telescope, and other space-based laboratories. They'll be in the newspaper (if we still have newspapers). You wait.

1.5 How QS&BB Will Work

Here's how QS&BB is going to work. As you read through the book you'll see a number o f repeating features: Goals, Biography, Sides, Flags, Notebooks, Diagrammatica, and the Crank. Let's see what these each are.

1.5.1 Goals

The first section of every chapter will itemize three categories of goals that I hope you'll achieve. After completing each chapter, I hope you will:

- **Understand**. This will often mean some facility with a set of calculations and/or graphics interpretation. It means that you've followed a simple mathematical argument interactively (see Notebooks, below). For example to **Understand** a recipe means that you've prepared a meal using it. It doesn't mean that you created it.
- **Appreciate**. This is less quantitative than **Understanding**. To **Appreciate** a recipe you would realize that to sweeten it you'd add sugar, but not actually do it or even predict exactly how much.
- **Familiarize**. This is a fly-by of some story or feature of a bit of our physics story. To be **Familiar** means that you know to go to Mr Google for information, because you can't remember the details before that step. Continuing with the food analogy, you might be **Familiar** with the idea that recipes for chocolate cookies exist, but you'd need the web or a cookbook in order to **Appreciate** or **Understand** one.

1.5.2 Biography

I'll bet you might think of physics as strange symbols and dry prose memorialized between the covers of big books and journals. But at its most basic, what is physics? It's people. Scientists carry on daily tasks, most of which are routine and not very risky. But every once in a while exceptional people accomplish exceptional things—they see some phenomenon or interpret some idea differently from everyone else.[37] This is a stressful place to be! Our heroes—the ones in textbooks—pursue their visions sometimes at personal cost.

[37] Everyone I work with is smart. But there have been some scary-smart people in the history of science and I'd like for you to meet many of them.

I've found that sometimes the content of the physics stays in students memories because they associate it with the people, so rather than stick a little scientific biography in a sidebar like many books, I highlight the people. The second section of each chapter includes a story: "A Little Bit of Einstein" (or someone) will introduce you to someone you've heard of ("A Little Bit of Einstein,"A Little Bit of Newton," and so on) or someone maybe you've not ("A Little Bit of Huygens," "A Little Bit of Kepler," "A Little Bit of Dirac," and so on).

Now while many of these folks are pretty special—and indeed some were a little odd—most were just everyday people with skills. That's most of us.[38] I'd muck up the preparation of a legal opinion and you wouldn't want me to treat you for an illness. Those are skills practiced by others. My colleagues and I have different skills, no fancier than those required of many other jobs. We're moms and dads, mow the yard, and fix dinner just like everyone else. But we have these heroes to whom we're professionally connected[39] our chapters will highlight them. I hope you enjoy this part of QS&BB.

[38] Perhaps you're not surprised at my impatience with the "mad scientist" image. Marty McFly's friend, Doc Brown, is my least favorite example of a scientist.

[39] A fun exercise that all of us have played at some part in our lives is to trace our Ph.D. degree supervisor, to his or hers, and so on back in history. For example, mine was Lincoln Wolfenstein. His was Edward Teller, who came from Werner Heisenberg, who in turn came from Arnold Sommerfeld, who came from Ferdinand von Lindemann, who came from Felix Klein, who came from Julius Plücker, who came from Christian Ludwig Gerling, who came from Carl Friedrich Gauss who came from Johann Friedrich Pfaff who came from Johann Elert Bode who came from Johann Georg Büsch who came from Johann Andreas Segner who came from Georg Erhard Hamberger who came from Johann Adolph Wedel who came from Georg Wolfgang Wedel who came from... well, you get the idea.

1.5.3 Sides

Pay attention to what appears in the side margins. To your left are examples of the items that will appear regularly.. Footnotes[40] will be there, for easy reference. Side comments—sometimes even serious ones—will be placed in margin notes. Little, tiny essays. And there will be three kinds of named sidenotes: definitions, equations, and constants.

[40] Here's a footnote.

Just a regular margin note here.

Definition: Some word.
Followed by the definition of that word.

Equation: Tee shirt equation.
$E = mc^2$

Constant of nature: A constant of nature..
Gallon = 4.0 quarts.

[41] And hopefully, sometimes hysterical.

There's a lot of jargon in this business and so I'll call out words or phrases that you'll need to keep in mind for later use. Those will get the name definitions, just like the dictionary.

There are also a handful of equations that will be useful and so when one of them appears in a margin, take it seriously. You'll need it. In fact, as you'll see below, I'm serious about taking notes and frankly copying the definitions and equations in a notebook, which you'll add to with each chapter, would be a good reference for you and an extremely important part of mentally processing what you write. So: write them for exercise and for safe-keeping.

1.5.4 Flags

While our coverage is largely historical[41] we'll come across ideas and concepts that will play various important roles as we move through the decades. These I call "flags" and they appear in the text, and then will be recalled at the back of each chapter so they will all be in one place. There are four kinds of flags:

A concept is just what it sounds like: an important idea worth highlighting. *Key Concept 2*

An observation is an experimental fact of profound consequence. *Key Observation 1*

A question is just that: something that we need to understand. *Key Question 6*

Then there is a particle-flag. We'll be accumulating a number of particles as we go along and I will provide this table each time. For example, the electron was discovered in 1895 and the particle-flag for it will read:

Particle 1

Electron

symbol:	e				
charge:	$-1e$	mass:	$m_e = 0.511\ \mathrm{MeV/c^2}$	spin:	$1/2$
category	fermion			category	elementary

1.5.5 Notebooks

Actually, there is much of this account that I *don't* want you to "read" in the normal way. I want you to walk through the book—like the phone book—with your fingers doing the walking.[42] One thing I've learned over a few decades of teaching smart students who study subjects that are not mathematical (you?) is that if you come to the university as a freshman to major in, say Political Science or English or Psychology... that initial semester of college might be the first time in 13 previous school years in which you aren't taking a math course. At that point, after about a year away, you might find that your math muscle has atrophied. Trust me, I'm a doctor. You do have a math muscle and it needs periodic exercise to keep it fit.

[42] There used to be this book. It had phone numbers, names, and addresses in it. The Phone Company's slogan was "let your fingers do the walking." This seems a century ago.

Just like I can't do 100 pushups any more—and I'd be pretty anxious if I were asked to do that in front of a class—I know that you might not be able to do some mathematics that you once were able to do! That's the famous "math anxiety."

I'm convinced that your brain is directly wired to your fingers.[43] Unless you've spent many years at this, you really can't *read* mathematics like you might read a history textbook: you have to interact with it. There is an enormous cognitive benefit from tactile reading: forming the symbols and numbers along with the text and allowing the logic to happen in your brain *by writing it out*. So this book will urge you to participate in the mathematical story-telling and I've got two ways for you to do it.

[43] Or is it only my brain?

The Pencil.

The first way is by following along with your fingers: Buy a spiral-bound notebook into which you'll record your reading notes.[44] Then, when you're reading, you're using a pencil.

[44] Or your instructor might wish for you to use the template at the end of this chapter for your work. Notice that the "Pencil" has a number and that would be transferred to your paper.

When I get to a point in the text where need you to use that direct connection from your fingers to your brain, I'll indicate it with:

Pencil 1.1. ✎

What will follow the pencil will be short sections of content where you need to drill down a little deeper than what just passively reading will do for you. To me that means, start recording detailed notes. In fact I'm happy if you even *just copy* the numbers and formulas and that will be good enough. It will still penetrate your brain...in a good way.

👍

When it's done, I'll congratulate you with a thumbs-up and you can go back to just reading.

I guarantee you that if you don't do this and simply kick back and read without pencil in hand, what comes after will mean less. Further, I can guarantee you that if you *do do this*, the logic of the mathematics and the inevitability of the narrative will be escorted to your brain and be there when you need it later.

The You Do It

The second way is more active and requires you to actually fill in blank spaces in the book. For example, I will sometimes come across an algebraic equation that needs to be manipulated a little or evaluated by plugging in numbers in order to keep going with the narrative. Or I'll have a graph that we need to look at for a specific number or an ordering exercise that will inform the narrative. When this happens, you'll see a QR code, some short instructions, and some white space. That tapping sound you'll hear is me waiting for you to fill the space.

You Do It 1.1. Example QR

or copy the solution

This is an example of the kind of thing that you'll see: Newton's Gravitational Law is $F = G\frac{mM}{R^2}$.Solve for G.

The You Do It will include enough blank space for you to actually do the manipulation. The QR code (or the link underneath) will provide you with a smartphone screen-sized derivation or some written coaching as to what you should write in that blank space. The idea is that first *you try it on your own*, then you use your phone to see how I did it.[45] Even if you simply copy what your phone shows you symbol by symbol, there's still a huge benefit to your understanding the physics. It will be in your brain, through your fingers. I *want* you to copy my work!

[45] If you can't make the QR code work, or don't want to, the phrase underneath it "or copy the solution" is a hot link in the pdf version of this document and when clicked will take you to the QR code's destination.

Wait. *I know how to read. Do I really have to do this?*

Glad you asked. *No, of course not. But if you can absorb what's coming without your pencil connecting to your brain then you're a lot smarter than I am. Take a chance. Write in your book. I won't tell.*

1.5.6 Digrammatica

I will need many diagrams. Sometimes these will be graphs of characteristic physical quantities (like distance versus time). Sometimes, these will be diagrams of phenomena (like an electric field). Sometimes these will be iconic items that go together in useful ways, like Feynman Diagrams. Rather than interrupt the flow in the narrative, I'll follow that chapter of interest with a special kind of chapter which I'll call *Diagrammatica*.[46] The contents of Diagrammatica chapters will be little more than a descriptive inventory of the diagrams of interest. Don't expect much lyrical prose in the Diagrammatica chapters. They're all business.

[46] The name is actually borrowed from a venerated little book on Feynman Diagrams by Nobel Laureate and University of Michigan Physics Professor, Martinus Veltman ("Tini"), *Diagrammatica: The Path to Feynman Diagrams (Cambridge Lecture Notes in Physics).*

1.5.7 The Crank

Finally, in a course like this the emphasis is not on the details of calculation but on the conceptual ideas. But calculations do happen and I think we should be able to identify what goes into a particular calculation and what comes out. In Chapter 2 I'll talk a little bit about models and the scientific process. Every prediction includes the following components:

- A Hard Core of unquestioned assumptions, models, data, and so on. A modern publication in aerodynamics doesn't need to go back and justify the use of Newton's laws of motion. It's assumed to be correct. So there is always a Core.
- Sometimes a prediction requires mixing data with mathematics. So an input might include Data.
- Every prediction is a prediction of a model, sometimes as a test of the model and sometimes as a test of an experiment. So the primary input are the ingredients of a Model.
- Most calculations involve a strategy of how to proceed using the Core and the Model.
- Then, there is a result! A prediction can be purely mathematical (we'd say "theoretical") and so the calculation really is a test of the logical consistency of the Model (does it "hang together"). Usually though, we expect the outcome to predict the results of some measurement.

I know that you've all used the phrase "turn the crank." The assumption is that somewhere someone simply followed through with the rules of a mathematical calculation. Well, a crank is so 19th century! I'll repeatedly use a graphic of a nonsense circuit that uses a little fictitious microprocessor[47] which is doing the crank-turning. Figure 1.5 is my silly image which will emphasize the inputs, what's being tested, and the conclusion. We'll take it for granted that someone with the right expertise can turn that crank, just like a computer might. You'll see how this works in the next chapter and then in many to come.

[47] I've plopped on top of my nonsense circuit an FPGA (Field Programmable Gate Array) from Xilinx Corporation. This is their newest model, the UltraScale+™.

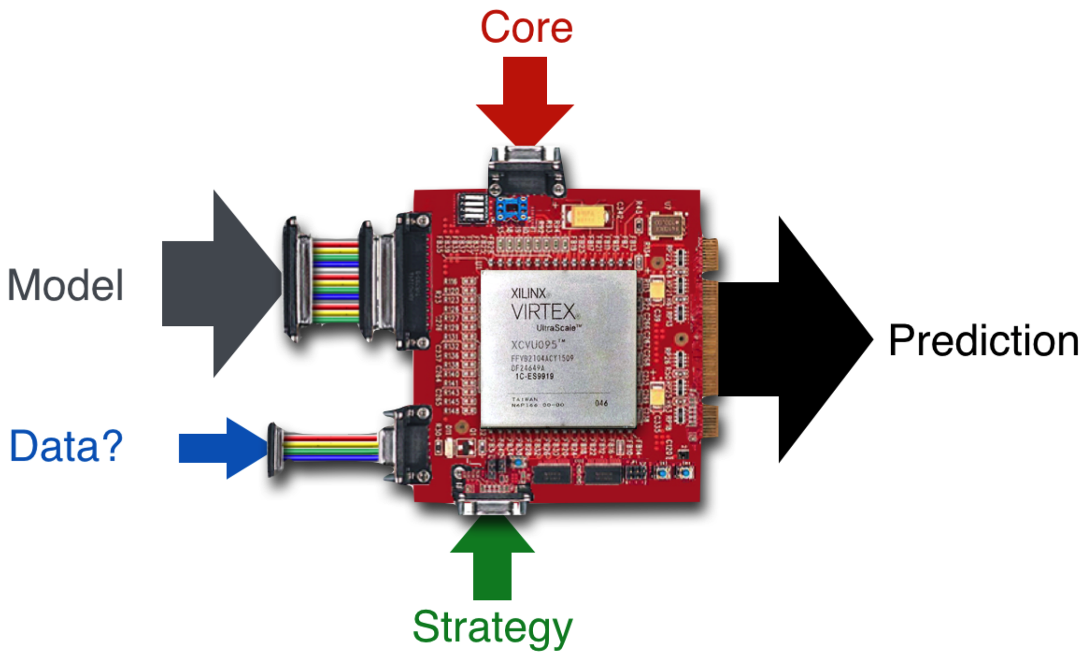

Figure 1.5: Our QS&BBcrank. The inputs are the Core, the Model, and sometimes Data. The outputs is some prediction. The Xilinx FPGA is essentially a little computer-on-a-chip used in many industrial and research applications, including those designed at MSU for our CERN ATLAS experiment.

Here's an example. In the early 18th century Newton's ideas about momentum and mechanics were being tried out on various phenomena. Daniel Bernoulli, a part of the most dysfunctional scientific family in the history of physics[48] had the idea that maybe the pressure that gases exert on a container were a function of collisions that hypothetical gas molecules exert on the walls of the container. This idea was expanded on later and actually resulted in a new understanding that temperature is nothing more than the average kinetic energy of a gas. This explained Boyle's Law, which maybe you remember from high school. It says that $PV =$ constant. Figure 1.6 is how I would short-circuit the calculation that one would go through to reach this conclusion. Get it?

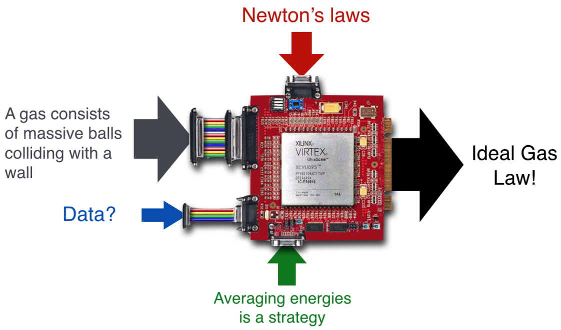

Figure 1.6: Newton's laws were not questioned, and so the Core. The Model was that a gas is a collection of tiny, massive balls that collided with the walls, and the strategy was to not treat each of them individually, but to average over their motions.

[48] Look them up! `http://www.daviddarling.info/encyclopedia/B/Bernoulli.html`

1.5.8 QS&BB Organization

I've organized QS&BBinto four Parts.

0. **Tools** We'll use minimal mathematics and the next chapter stands alone as a refresher (and hopefully, a calming influence) for all that we'll need to follow QS&BB.[49]
1. **Physics and Cosmology of my Grandparent's Generation.** Before the turn of the 20th century, known physics included the well-confirmed physics of Newton's mechanics, optics, and the relatively new electromagnetism. These subjects form the language for all of the 20th and 21st centuries and are the individual points of departure for the revolutions to come. We'll need to establish our foundations in these subjects.[50]
2. **Physics and Cosmology of My Parent's Generation.** From 1900 through the 1950's everyone was becoming comfortable (as much as possible!) with the quantum mechanical and relativity theories...and their merging in Relativistic Quantum Field Theory. These subjects are our theories, and our models all respect their rules.[51]
3. **Physics and Cosmology of My Generation.** Since the discovery of the fact that the universe is filled with microwaves left over from the big bang and that two of the most different-looking theories are actually a part of a single story, we've been hard at work on puzzles that these discoveries create. This is our work today.[52]
4. **Physics and Cosmology of Your Generation.** We are intensely pursuing a number of observational puzzles and inspired and compelling theoretical ideas. We will look to the future.[53]

[49] Chapter 2.

[50] Chapters 3 through ??

[51] Chapters 15 through ??

[52] Chapters 19 through 30

[53] Chapters 31 through 32

Okay. I lied. Five parts, but the first one doesn't really count as an actual part.

> What I need from you is an open mind and your pencil. Work the examples, do the Pencil-and-Thumb fill-ins, and enjoy our exploration of Outer and Inner Space.

Let's go to work!