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Quarks,
Spacetime,
and the Big Bang

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"Nature Loves to Hide"

Heraclitus

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 in its own way.[1]

Creating courses for non-specialists in the sciences is especially challenging, but it's important because many of society's big problems are scientific at their roots.[2] An informed citizen needs to understand some scientific facts, while also appreciating the scientific method: 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 mathematical) 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 are 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. Once we've passed through a gentle introduction to motion, collisions, electricity, and magnetism, the light-algebraic 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 T-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 and I have fun doing it. I'm lucky enough to be continuously supported by you[4] for my research in particle physics for three decades and I'm grateful. In some ways, this book and course are in partial repayment for that support.

[4] The National Science Foundation, specifically.

I've never met anyone who didn't share my curiosity in wanting to know how the universe works. Even after a lifetime immersed in these matters daily, 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 as we work 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.

QS&BB Organization

I've organized QS&BB into 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.[6]
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.[7]
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.[8]
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.[9]
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.[10]

[6] Chapter 2.

[7] Chapters 3 through ??

[8] Chapters ?? through ??

[9] Chapters ?? through ??

[10] Chapters ?? through ??

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

The Nitty-Gritty of QS&BB

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.

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.

Biography

I fear that 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, physics is about people. Scientists carry on daily tasks, most of which are routine. But every once in a while, *exceptional people* accomplish exceptional things—they see some phenomenon or interpret some idea differently from everyone else.[11] This is a stressful place to be! Our heroes—the ones in textbooks—pursue their visions sometimes at personal cost.

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).

Although 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.[12] My colleagues and I have different skills, no fancier than those required of many other jobs. 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. 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[13] our chapters will highlight them. I hope you enjoy this part of QS&BB.

[11] 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.

[12] 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.

[13] 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.

Sides

Pay attention to what appears in the side margins. To your left are examples of the items that will appear regularly.. Footnotes[14] will be there, for easy reference. Side comments—sometimes even serious ones—will be placed in margin notes. Think of them as little, tiny essays. And there will be three kinds of named sidenotes: definitions, equations, and constants.

[14] Here's a footnote.

Just a regular margin note here.

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

Equation: **T-shirt equation.**
$E = mc^2$

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

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 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.

Flags

Though our coverage is largely historical,[15] we'll come across ideas and concepts that will play various important roles as we move through the decades. I call these "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:

[15] And hopefully, sometimes hysterical.

A concept is just what it sounds like: an important idea worth highlighting. *Key Concept 1*

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 1*

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

Notebooks

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.[16] 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.

I'm convinced that your brain is wired directly to your fingers.[17] 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.

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.[18] Then, when you're reading, you're using a pencil.

[16] 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."

[17] Or is it only my brain?

[18] 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 0.1.

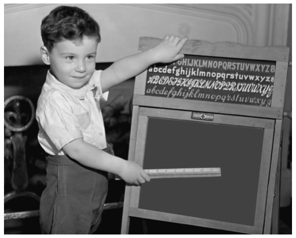
What will follow the pencil will be short sections of content where you need to drill down a little deeper than what just passively reading will do for you. To me that means, start recording detailed notes. In fact I'm happy if you even *just copy* the numbers and formulas and that will be good enough.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

The second way is more active and requires you to actually write along with me. 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 little boy pointing at his blackboard and some instructions…your clue to get out your pencil again, but this time on your own for a minute. That tapping sound you'll hear is me waiting for you to write it out.



You Do It 0.1.
introduction/SolvingNewton1

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

The idea is that first *try it on your own*, then you can click on the blackboard and I'll walk you through it in a movie. Even if you simply copy what I write 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!

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.*

One more thing. The title under the picture includes a part of a directory. For this example, it's "introduction/SolvingNewton1." If you cannot click on the image, you can go to the movie by from the QR code in the margin (which provides the root https://qstbb.pa.msu.edu/storage/QSBB_WebManuscript/) and appending the final address location or directly by typing it all into a bookmark. The complete path to the movie is then the combination of the root (which is common throughout the book) and that portion in the title of each You Do It caption. For this one it would be:
https://qstbb.pa.msu.edu/storage/QSBB_WebManuscript/introduction/SolvingNewton1 .

Get it?

Figure 2: The QR code points to the root directory for movies.

Digrammatica

We 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*.[19] 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.

[19] 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)*.

Turning 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[20] which is doing the crank-turning. Figure 3 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.

[20] 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+™.

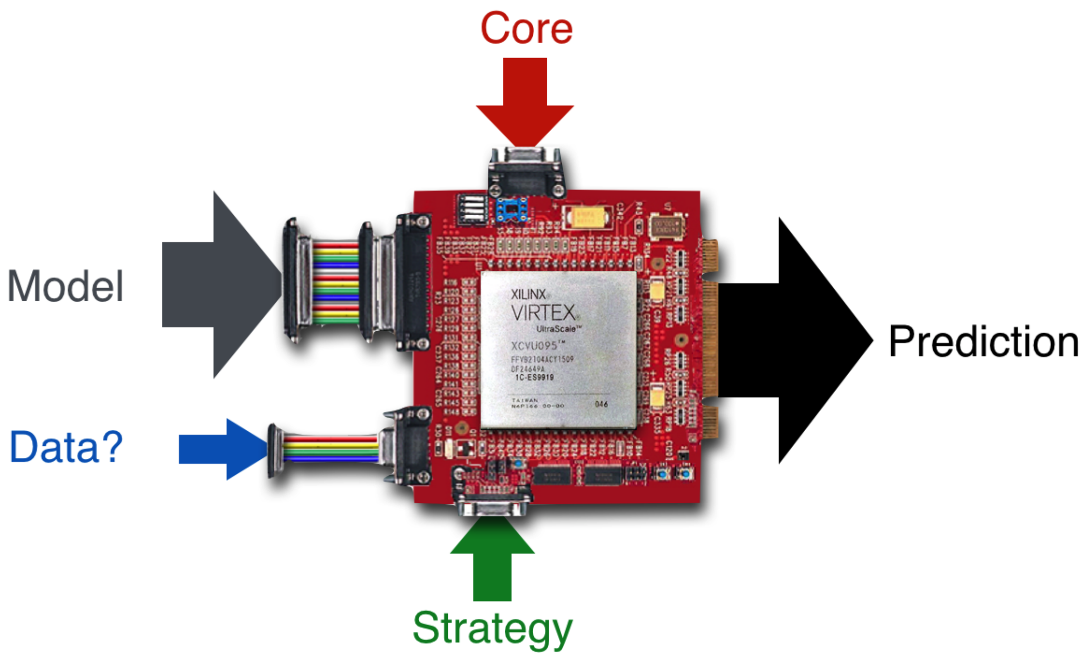


Figure 3: Our QS&BBcrank. The inputs are the Core, the Model, and sometimes Data. The outputs is some prediction. The Xilinx FPGA is essentially a little computer-on-a-chip used in many industrial and research applications, including those designed at MSU for our CERN ATLAS experiment.

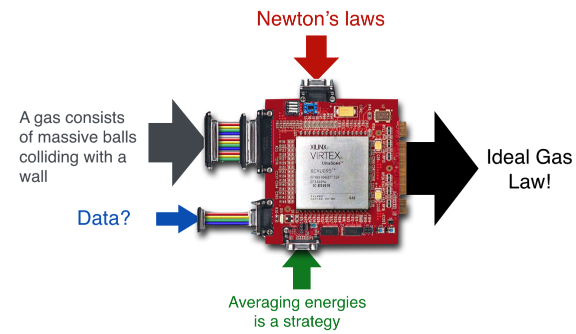


Figure 4: Newton's laws were not questioned, and so the Core. The Model was that a gas is a collection of tiny, massive balls that collided with the walls, and the strategy was to not treat each of them individually, but to average over their motions.

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[21] 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 4 is how I would short-circuit the calculation that one would go through to reach this conclusion. Get it?

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

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!