# The Shifting Terrain of Scientific Inquiry

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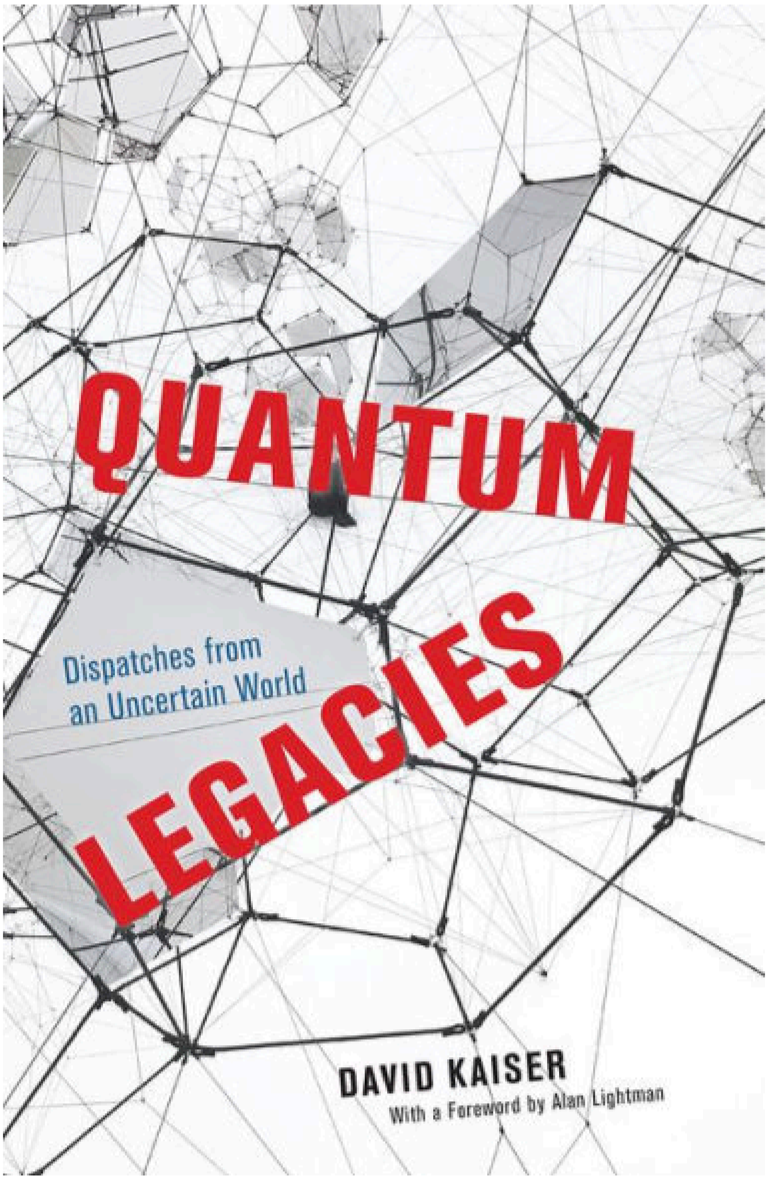
## THE SHIFTING TERRAIN OF SCIENTIFIC INQUIRY




I have a couple of questions that are on my mind these days. One of the things that I find helpful as an historian of science is tracing through what questions have risen to prominence in scientific or intellectual communities in different times and places. It's fun to chase down the answers, the competing solutions, or suggestions of how the world might work that lots of people have worked toward in the past. But I find it interesting to go after the questions that they were asking in the first place. What counted as a legitimate scientific question or subject of inquiry? And how have the questions been shaped and framed and buoyed by the immersion of those people asking questions in the real world?

One example that's still on my mind is this question of what to do about quantum theory. Quantum theory is by any measure our most successful scientific theory in the history of humankind, going back as long as we choose to go back. Predictions using the equations of quantum theory can be formulated in some instances out to exponential accuracy. We can now use fancy computer routines to make predictions for the behavior of little bits of matter, like electrons and other subatomic particles, and make predictions for their properties out to eleven, twelve, or thirteen decimal places. It's an extraordinary level of precision. And then other enterprising researchers can subject those predictions to measurement on actual electrons in a real laboratory and check the answers. The measured results and the theoretical predictions in some of these instances will match out to a part per trillion, to one part in $10^{12}$. By these kinds of measures, quantum theory is just unbelievably powerful and impressive. And yet, as a story about nature, the conceptual picture that quantum theory seems to suggest is very far from clear. It's been far from clear now for about a century. It's not that no one has any idea; it's that lots of people have lots of ideas. To this day, there's a real contest of people trying to make sense of what these impeccable equations imply about how the world works.

All that is to say that this is now a topic of ongoing interest and attention among researchers around the world in virtually every continent. And yet, that basic question—what does quantum theory tell us about how the world works?—was ruled out of court as a legitimate subject of scientific inquiry for large periods of time over the century that we've been grappling with quantum theory.

We have this paradox where everyone agrees that quantum theory is this crowning achievement, but what do we do with it? What kinds of questions is it legitimate to even pose about it? Those have not always been so uniformly pursued, welcomed, or even acknowledged. Why did certain questions or aspects of that topic come into focus, even get tackled by leading members of the field? And why was it at other times seen as something to be pushed aside? And then by force, we have to begin broadening our inquiry. It's not only about the force of individual personalities or the grandeur of certain ideas. We start having to ask about things like the embeddedness of this enterprise in a very real and shifting human world—in a world of specific institutions and shifting geopolitics, lots of things about the broader framing within which we try to learn about nature. Those start to help us make sense of this shifting terrain of which questions get counted as legitimate. I find that constellation of heady ideas and how the embedding of those concepts and questions becomes a much more historical, much more human story, endlessly fun and very fascinating.

It's interesting to reflect on the uncertainties that we're facing amid the Covid-19 crisis. Many of us now are unavoidably stuck in the midst of an irreducible uncertainty that many people aren't very comfortable with. On one hand, as a physicist and someone who's been looking at the history of physics for a long time, quantum physicists have been grappling with the implications of Heisenberg's famous uncertainty principle for nearly a hundred years. We've become accustomed to necessary trade-offs. We could try to learn a lot about one thing, but necessarily know nothing whatsoever about some paired quantity. What does that do for our notion of how the world works, about making predictions for what will happen tomorrow or the next day?

On one hand, quantum physicists have a professional immersion in uncertainty. On the other hand, I don't know that we're so much better prepped to deal with, say, the Covid-19 situation than many other people, by which I mean the following: We can use our equations of quantum theory, for example, with the uncertainty principle baked in at the start to make very definite statements or predictions about how the world should work (at least under carefully controlled laboratory conditions). Then we can perform not just one or two measurements, but tens of thousands on systems that we prepare in the same way. We can test ideas to very high statistical significance. So, we can say that the world goes like this and not like that, at least not like that to one part in a million or one part in a trillion. That level of being able to frame a question carefully, go out and poke the world in clean laboratory conditions and try to sift through gobs and gobs of data points to get some real bedrock confidence in the outcomes—that's not the world we're in these days.

For all the talk about conceptual uncertainty and the uncertainty principle itself, there's on one hand a familiarity with not just uncertainty, but with probabilities, with being limited to making probabilistic predictions for the future. That's an analogy to where we all are these days with the course of the pandemic and how the world might eventually reopen. On the other hand, physicists, with our luxury of quantification and precision, are not in that sense much better off than most anyone else these days.

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I am an historian of science. I write books and articles, I go to archives, I interview people, and I try to put together arguments and interpretations of events from the past that help us inform ourselves about the present. I publish in history journals, I train history students, and I love it. I'm also a member of the Physics Department at MIT. I teach physics courses and I advise a research group in physics, so I get to wear more than one hat.

The field of history of science has been a terrific professional and intellectual home for me for a long time. Most historians of science consider themselves historians first. That is to say, we want to craft compelling interpretations and arguments about the past, about why and how things have changed in human history. Our focus is on efforts to try to make sense of the world, what we would now call scientific research. It's gone by other names in times gone by—the fields of natural philosophy, or natural history, or other terms that were once more commonly used. How has that inquiry unfolded? How has it changed? How has it been embedded in a sometimes much broader human society and been buffeted by politics, culture, and institutions?

Most historians of science, certainly these days, consider themselves historians. That means we use historical methods of research. We comb through the published literature, investigate unpublished things—correspondence, notes, notebooks, grant proposals. For more recent periods, we interview people. (There's a colleague of mine who likes to say that the historian's job is reading dead people's mail, which captures a lot of what we try to do.) We are trying to figure out the texture of lived experience and how that informed the people about whose world we're trying to get our heads back into. On one hand, it is an interpretive effort squarely within the humanities and social sciences to make sense of our world in times and places gone by. With the history of science, we get to have this productive, ongoing discussion with much more contemporary events and efforts in the sciences today. Why do certain ideas take hold and become so prominent? Why do certain questions rise to prominence and get asked in one setting versus another? These are the larger questions about the present-day scientific enterprise that a lot of work in the history of science can help us better understand.

There's a long history of researchers trying to relate their work to broader audiences for different motivations, using different media and techniques. Historians of science have learned a lot about science communication among fellow scientists. That's an example where some of the insights from historians of science might be valuable even to this day. In my own work, I get to play with these ideas from recent physics in a few different ways: I conduct historical research; I do comb through dead people's mail and sometimes live people's mail; I get to interview people. A lot of my historical work is from fairly recent times, so I get to talk with people more directly in email and so on. But I am also a physicist and conduct physics research for physicists' sakes. I consider myself lucky to get to play with ideas that themselves have been bumping along in different ways and been seen from many different angles in different times and places.

On one hand, the historical work doesn't tell me what to do today when I wear my physicist's cap, but it does sometimes give me an appreciation for how certain questions have been posed, or maybe unforeseen trends that might bubble up if we change our view and take a look from a different angle. In that sense, I get to play with contemporary questions about, in my case, theoretical physics.

One of the things that historians can do even for contemporary scientific research is not to offer a better candidate answer—I don't think that's something to look for from the historical record or from historians themselves—but they can help remind us of questions or methods that had once ignited the imaginations of prior generations. Some of the questions have a much longer shelf life, let's say, than the proposed answers. Some answers look great a century on, and we're delighted to put them in our textbooks and teach them to our students. We know, however, that in general most answers are going to look foolish or more often just irrelevant after a rather modest passage of time.

Focusing on the leading scientific suggestions of today has value, but it's limited. Instead, one of the tasks historians can do is remind us of the questions that had once seemed so urgent. We will see the question from a different light today than before, but there can be an intergenerational continuity, a genuine intellectual value for chasing down the connections among the questions, even more so than worrying too much about the proposed answers, which we know are going to have a much shorter shelf life.

I've been thinking in recent years about writing about the recent history of science and the many kinds of people we might be able to engage with such writing, or hopefully even excite or sometimes inspire. What are the kinds of venues for that? What are the styles? What might click with one audience and maybe not quite land with another? I've been trying to think more explicitly about the craft of writing itself. In my career, I've written a book with a big trade press, I've written books with university presses, I've written books that were specialist monographs within university presses. Beyond the monograph, beyond the book, I've enjoyed being able to write for a variety of magazines and newspapers and broader audience venues— shorter essays, op-eds, and so on. The genre of the essay is a classic form; it's not like it was just invented recently. There are some people who make it look so easy. They're just such natural essayists. There are people who can capture complicated ideas full of human drama and struggle and convey that in a way that respects their readers, but doesn't expect the reader already to be an expert in the topic.

I have my personal favorites, and I think we're all inspired by writers like that. I've been trying to think more about what kind of communication might be successful with different readers and excite different conversations. It's dearly important to be able to write the focused monograph for my colleagues in the history of science or students who are going to encounter a textbook, and that has to have lots and lots of endnotes and all the so-called scholarly apparatus. It's equally as important to be able to write both books and articles for broader groups of readers for whom this might be the only thing they ever read about black holes, or the Big

Bang, or quantum entanglement, or for whom they would read this and then maybe be curious to read a few more things even though they're not going to make a career in theoretical physics.

One thing that I find helpful in thinking about writing, especially for that larger, more mixed heterogeneous group, is thinking about humans. So many of the ideas that I am frankly obsessed with in my own research, both as an historian and also as a physicist, concern scales that are so different, so strange or distant from the human scale. I do a lot of work on quantum theory with colleagues—on super fancy, crazy fun tests of quantum entanglement. I also work on cosmology and the grand sweep of the universe from the Big Bang to today—very dramatic cosmic processes in astrophysics. Neither of these are easy to convey to people who aren't trained in physics or in highly quantitative patterns of thought. So, what I find helpful is to bring humans into these accounts by trying to craft some careful metaphors and analogies.

There's a human element to the investigation into how we even came to ask those questions or muddle toward our answers. There are ways that convey some of the intellectual, conceptual heft about processes in the world that we've now come to learn quite a lot about, but to bring it to a human scale to convey what we think the stakes are, what genuinely keeps us up at night and gets us out of bed in the morning.

There's an importance to convey why we ask these questions so relentlessly, why we can seem so consumed and even obsessive; why we always have to come back to the public one way or another to ask for more resources to support what becomes very expensive scientific research, to convey why we think it matters, what we think we're after, and to convey it in a variety of forms for our fellow specialists, our budding students who are going to learn so much more than we'll ever know, and for our fellow readers and citizens. We scientists and historians have an obligation or responsibility to explain as clearly as we can why we think that's a worthwhile endeavor. Those all call for different kinds of writing, different scales of an argument, different techniques for composition, but they're all important. I've enjoyed trying to practice and get a little more experienced in each of those domains.

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My academic journey began like many academics do, which is say thanks to a large number of inspiring, patient, and generous teachers and mentors. That's how most of us get our start. For me, I had great teachers even through high school. Even as a teenager, I caught the physics bug and got hooked on that in large measure thanks to some wonderful popular books that grabbed me during the eighties. These were books like Heinz Pagels' *The Cosmic Code*, one of my all-time favorites, or books by John Gribbin that were just coming out.

I encountered *The Cosmic Code* when I was a teenager, and it's almost as if it didn't let me go. It introduced me to ideas, some of which I still grapple with in my professional life. As some folks might remember, it wasn't meant to be an exercise in the history of science, but Pagels was so good at finding these telling analogies and metaphors to bring abstract or difficult-sounding ideas to a human scale and to multiple kinds of readers. He captured a bit of the drama of the urge to know that was driving generations of researchers since late in the 19th century, throughout the 20th. I was just hooked. It was a gateway drug for me.

Likewise, John Gribbin had a series of wonderful books back in the eighties (of course he's written many since then). There are people I get to work with today about whom I was learning as a high school kid because their ideas were already showing up in some of these high-quality broad readership books about modern physics in the eighties.

Already a confirmed physics enthusiast, I went on to study physics in college. I had some amazing teachers and mentors there, one of whom took notice of my interest in these human stories, telling me that there were people who did that for a living called historians of science. One of my physics mentors, Joe Harris, was the one who told me that if I like those additional ways of engaging with the study of nature to go talk to actual card-carrying historians of science. And there were some marvelous ones right on campus. Naomi Oreskes became one of my most important mentors as an historian. She was a very young professor then and took me under her wing. Rich Kremer was another.

Even as an undergraduate, I began studying both theoretical physics and the history of science pretty intensively. Following Naomi's example—she had been a graduate student at Stanford, and she did a PhD in earth sciences and geology and a PhD in the history of science—I thought maybe I should try that too. She was an existence proof for me and a very direct inspiration. Late in college, I decided that I'd love to try to put together an academic career to see if I could keep these two kinds of inquiry going, if I could try to learn more and maybe contribute both as a theoretical physicist and as an historian of science. I wound up applying to three schools for graduate school, but I applied six times. At each institution, I applied both to the program in the history of science and to the program in physics. I was enormously lucky to study with mentors like Peter Galison, who was my main history advisor, and Alan Guth, who was my main physics advisor. Peter had been Naomi's mentor on the history side. He had also done two PhDs, one in physics, one in the history of science. Again, I had the benefit of extraordinary intellectual mentorship, but also help with the nitty gritty logistics: What does it mean to study more than one thing at a time? And how do you try to craft a career like that?

The academic market when I was hitting it was pretty dismal—it's pretty dismal again today—so it really was not to be counted on. But I did get a very lucky break. There was a position open at MIT and they were foolish enough to hire me. I've been on the faculty at MIT now for twenty years as a professor, both of the history of science and also professor of physics. I get to work with students and research collaborations of my own in each field.

That's how I got to be where I am and why I get to grapple with things like quantum mechanics, the Big Bang, and black holes from a number of different points of view. These days, on the physics side, I mostly work with Alan Guth, my own very dear mentor from my graduate-school days. We have a research group that we advise together now in the MIT Center for Theoretical Physics. We study the very early universe—around the time of the Big Bang when the universe was, roughly speaking, about a billion, billion, billion billionth of a second old. It's a very different sense of time for what kinds of physical interactions we want to think about and try to study.

There's an amazing amount that the whole community in cosmology has been able to learn in the last twenty to thirty years. And it's a thriving field with new data coming in, new experiments and observations, and still no shortage of challenging, bizarre, and sometimes quite delicious ideas. I'm still swept up with things that I first began learning about, in that sense, going back to my high school days. On the history side, I'm still very interested in how we've come to ask these questions about the universe, about the cosmos. I'm very slowly working on a book project about Einstein's general theory of relativity, which is by any measure his crowning scientific achievement. It's the framework within which, even to this day, a hundred years on, we frame our questions about things that Einstein himself had never even heard of or thought about.

One of the things that I'm excited about and I've been able to work on for the last few years is trying to find more clever ways to test these very strange-sounding ideas about quantum theory. Are we forced to take on some of these very strange-sounding ideas not only because they make sense on our scratchpads, but because we have more solid evidence that the world works that way? One example of that, which was a highlight not just of my career but of my life to date, was working on a project that we called the Cosmic Bell experiments.

This grew into an international collaboration. It started as a discussion between myself, a post-doc named Andy Friedman, who I had just begun working with at MIT, and one of Andy's close friends from grad school days, Jason Gallicchio, who is now a professor of physics. It was the three of us shooting the breeze and wondering about questions about quantum entanglement and how people had tried to test it to see if the world works that way. And in pretty rapid order, we were able to build that into an international collaboration with twenty researchers, many colleagues on multiple continents. The upshot was that we found ourselves on top of a mountain using extraordinary telescopes with four-meter polished mirrors, thirteen-foot mirrors, staring out at the dark night sky on the island of La Palma, taking in light every millionth of a second—every microsecond—from two different, very distant, very bright quasars, some early-stage galaxies that are very far from us.

The light from one of those quasars has been traveling toward our telescope for 12 billion years. Our universe isn't even 14 billion years old yet. So, for most of the history of the cosmos, that light had been making its journey toward us, that we captured just that moment, that fraction of a second. On the other side of the sky, we took in light from a different quasar whose light began its journey about 8 billion years ago. This is some of the oldest light in the cosmos. We're taking in that light to ask a souped-up version of a question that physicists have been asking themselves for nearly a hundred years, and we were trying to find the most compelling evidence that we could to try to answer that question, or at least constrain the range of possible answers.

The question was one about whether quantum entanglement is a fact of the world or only an artifact of our current ideas. That is to say, is what Einstein famously called "spooky action at a distance" an inescapable fact of the universe, or have we somehow been misunderstanding a series of prior investigations and experiments? To cut to the chase, our experiments, much like the ones that had come before ours, show extraordinary evidence in favor of entanglement, that this is how the world works, like it or not. Some people still seem uncomfortable with the idea, and yet, the space of reasonable or logical alternatives has been shoved not just into a corner on Earth, but into a tiny region of space and time out of the whole universe before us.

By taking in that light on the mountaintop with these two gorgeous telescopes with our group, we were trying to ask this question about nature at its most fundamental, about pairs of particles created in special ways. Do the properties of those particles obey a sharpened sense of how the world should work as Einstein himself had developed, or do they defy that? Do they follow different rules, and do we just have to make our peace with it? Our investigation, like the ones before it, showed quite resoundingly that entanglement is a fact that we have to get our heads around because it's not going away. That's an example where there is an historical dimension going back to the 1930s and the 1960s—waves of people before our current generation, thinking as hard as they could about these kinds of questions, reformulating the questions.

On one hand, it has this historical mission. On the other hand, we're using state-of-the-art equipment with fancy lasers, and microelectronics, and atomic clocks down to nearly nanosecond accuracy. So, we have this instrumentarium of the high modern, of the most up-to-date instruments that my colleagues could either acquire or build themselves, and we're bringing it to bear on questions that are nearly a hundred years old. Every day I got to work on that project was undeniably a day of joy, and it's a journey that we're continuing. There are more questions in that vein that we're trying to puzzle toward.

One of my favorite things that I've been able to enjoy through writing in different modes for different audiences is hearing from folks I didn't otherwise know, who aren't colleagues in either physics or history, aren't academics, who happened to read a short piece I'd written and it really caught their eye. For example, I recently heard from someone I didn't know before who told me that his father had been a very prominent physicist at Caltech, someone whose name I knew very well. The son wrote to me out of the blue saying that this piece I'd written, that he just happened to read, brought his father's life work into focus in a way that their own discussions or family lore hadn't quite done. He gained a perspective on what drove his father and his father's generation. That's an extraordinary gift to get an email like that out of the blue.

I hope that my work will inspire some kids as I was so intensely inspired when I was a teenager by people like Heinz Pagels and other authors of that time. You hope you'll help ignite a spark in some very clever, eager, hardworking young folks. But to get a letter from a person who now himself is later in his years reflecting back on his family experiences, and the notion that I could help even in a modest way to make sense of his own world—that was just remarkable; I really cherished that email. That's the kind of response from many kinds of readers that I value, in that it helps me write the next piece. There's a readership out there who will hopefully get something out of these quirky tales of strange-sounding people, and that's a real gift.