*VOID*

## Foundational Questions in Science

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# VOID

## *The Strange Physics of Nothing*

James Owen Weatherall

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# *Prologue*
## Much Ado about Nothing

Imagine a house with no furniture. Is it empty? Presumably I haven't given enough information to answer the question. There may be other stuff in the house: people, clothes, food, pets. Take all of this away, too. Indeed, take out all of the "stuff," big and small. Mop the floors, scrub the bathroom, and dust the window sills. Now is the house empty?

If this were a book about real estate, the answer would likely be "yes." At least, the house would be ready for a new owner to move in. But is it really *empty*? Perhaps there's a sense in which the rooms are empty, but of course the house still has some things inside. It has walls and floors, pipes and electrical wires, toilets and bathtubs and sinks. Take all of this out, too—gut the house completely, imagining, for the sake of argument, that we could do so without the house collapsing. We are left with just a shell of a house. But is it empty?

Of course not. There's still air inside. And that's not all. If the house is located in a reasonably well-populated town, it is probably near radio towers whose signals reach the house. Perhaps the neighbors have a wireless network with a similar effect. If the house has windows, then during the day it may be filled with sunlight. Radio waves and light rays are kinds of electromagnetic radiation, so there is radiation in the house. And since the house is on the surface of the earth, if one were to drop an apple, say, it would fall to the floor due to the earth's gravitational influence. In classical physics, at least, this would be because there is a *gravitational field* inside the house.

Fine, you think. This is getting a bit pedantic. But we can deal with it. Put the house deep in intergalactic space, far from stars or any other massive bodies. Let the air escape and shield the house from radiation of all sorts. Surely *now* the house is empty. There is nothing inside. Right?

There is a very old question, famous, or infamous, for its difficulty. *Why is there something rather than nothing?*[1] Part of what makes the question difficult is that it's not clear what could possibly count as a satisfactory answer. Explanations have to start somewhere; this question, however, seems to demand that we explain everything at once, without appeal to anything that *does* exist.[2] For just this sort of reason, many scientifically oriented philosophers—not to mention scientists—have dismissed the question entirely. It makes sense, these philosophers would say, to ask *what* there is, how it behaves, how we have come to be in the current state of the universe from earlier states. Not *why*.

We are accustomed to looking to physics for our answers to these latter sorts of questions, at least at the most fundamental level. And indeed, physics has yielded some impressive answers: we now know the material world is composed of such things as quarks and electrons, photons and gluons. The physics of *stuff* is well-trod territory. But what of the alternative? That is, this approach, of asking what there is and how it behaves, puts all of the emphasis on the *something* half of the question and ignores the *nothing* half. What, according to our best physical theories, is nothing? What would the world be like if there were no electrons, no quarks, no photons?

It is this last question that will be the focus of this book. My goal is to explain that if we want to understand *stuff*, if we want to use physics to study what there is in the world, we need to reckon with what the world would be like if there weren't anything at all. I call this the physics of nothing.[3]

The question might seem silly. Nothing, after all, would just be what we'd have if there weren't any something. In a sense, one might think, no matter what kinds of stuff exists or could exist, the situation if there were nothing would be the same: empty space, pure and simple. This was how the great seventeenth-century physicist Isaac Newton thought about things. He held that space could be thought of as an infinite container into which stuff could be placed or removed without affecting the structure of space itself.[4] It was a kind of theater in which physics would unfold. According to this picture, the physics of nothing is simple.

In fact, this idea may seem *so* obvious as to pass by without much notice. To say that if we removed all the stuff in the universe, we'd be left with empty space doesn't seem like a substantive physical assumption—much less one that could be false. But this is as wrong as anything in physics could be.

The twentieth century was a tumultuous time for physics. Centuries-old theories were overturned, first by Einstein's discovery of special and general relativity between 1905 and 1915; then by the development, during the mid-1920s, of quantum theory; and again during the 1940s, when these two new theories were combined into what is now known as quantum field theory.[5] Little was left unscathed by these revolutions—even the physics of nothing.

Indeed, understanding how the physics of nothing has changed with the advent of general relativity and quantum field theory is essential to understanding both what these theories tell us about the world and how dramatically they differ from classical theory.

This book traces these changes. The first chapter picks up at the beginning of modern physics, with the work of the physicist and mathematician Isaac Newton during the seventeenth century. As I explain, Newton's best-known contributions to physics concern his theory of the motion of physical objects, as summarized in the laws of motion that bear his name. His theory of motion still forms the bedrock for a modern physics education, three and a half centuries later. But what is perhaps less well appreciated is that in order to even formulate his laws of motion, Newton needed to redefine fundamental notions of space and time. This led to a radical new picture of what the world is like—and also, what it would be like if there were no stuff in the first place.

One of my emphases here is just how controversial Newton's ideas were at the time. I explain how Newton broke with earlier physicists, such as the Greek philosopher-scientist Aristotle, whose thought dominated European science for millennia, and René Descartes, a French physicist, philosopher, and mathematician who strongly influenced Continental science in the early part of the seventeenth century. Much of the chapter is devoted to a famous dispute about the structure of space (and, as it will turn out, time) between Newton and one of his most accomplished contemporaries: Gottfried Willhelm Leibniz, a German polymath and court librarian in Hanover. As we will see, what appears at first glance to be a debate about metaphysics and theology is really tracking very subtle issues about physics—specifically, what we need to assume about space and time for motion to be the sort of thing that could be governed by laws in the first place.

In the second chapter, I turn to the first of two revolutions in physics from the early twentieth century: Albert Einstein's theory of relativity. Einstein's theory may be understood as a revision of Newton's laws of motion, mandated by the success of James Clerk Maxwell's theory of light, electricity, and magnetism in the nineteenth century. Maxwell's theory was originally formulated in the context of Newtonian physics, but this soon led to conceptual problems and surprising failed experiments. Einstein realized that Maxwell had really taken the first step on a path to a much more radical reconfiguration of physics. Like Newton, Einstein understood that the new theory of motion he was describing required him to redefine basic notions of space and time, leading to a new picture of the structure of (empty) space.

Revising Newton's laws of motion and setting them in a new spatio-temporal framework better adapted to Maxwell's theory resulted in what we now call *special relativity*. But Newton had done something else: he had also provided us with a theory of gravitation. Newton's theory had lasted a long time, with a long litany of successes. It could explain (almost) all of the observed motions in the solar system; it could also explain basic terrestrial phenomena, such as the tides and the motion of cannonballs. But it appeared to be incompatible with Einstein's new theory of space and time. The search for a new, appropriately relativistic theory of gravitation took Einstein another decade. The end result was the theory that we now call *general relativity*.

General relativity is striking for many reasons. It is a theory in which massive objects affect the motion of other massive objects.

In this way, it is much like Newton's theory of gravitation. But whereas in Newton's theory this motion arises because bodies exert a gravitational force on one another, in general relativity bodies affect one another by changing the geometrical structure of space and time. This is a theory in which space and time are *curved*, in the same way that a beach ball or the hood of a sleek car might be curved. And just as rain will run differently down a curved surface, so too will planets move differently through curved space and time.

The idea that stuff—stars, books, blue whales—changes the geometry of space and time is a significant shift from Newton's theory, or anything that came before it. But Einstein's theory allows even more: it allows for space and time to be curved even when there is *nothing* present, anywhere or at any time. In fact, space and time can themselves behave in ways that are strikingly similar to electromagnetic radiation, such as light or radio waves. As we will see, this makes defining what it would even mean for there to be "nothing" in the universe extremely subtle.

In the third chapter, I look at quantum theory—particularly at quantum theory in the context of a relativistic understanding of space and time. Like relativity theory, quantum theory may be understood as a revision of Newton's laws of motion. But it is a *different* revision, and the program of bringing relativity theory and quantum theory together is very much incomplete. For instance, we still do not have an adequate quantum theory of gravity because of profound difficulties in making quantum theory compatible with general relativity. But as I discuss, the problems arise at a much earlier stage, and although our best attempt to formulate a version of quantum theory that is compatible with special relativity—a theory known as *quantum field theory*—has had some of the most remarkable empirical successes in the history of science, there remain important ways in which the theory is not well understood.

Even so, one thing that *is* well understood (we think) about quantum field theory is that the physics of nothing plays a special role. This is because possible configurations of stuff in the world are described in terms of how many particles there are—or rather, by how likely we are to detect a given number of particles in a certain kind of experiment. To talk about these possible configurations of stuff, physicists begin by defining a special state of the world—known as the *vacuum state*—that is meant to represent a situation in which there are *no* particles and then go on to say how that state would change if you added particles of various kinds.

So the idea of a quantum vacuum is fundamental. Which makes it particularly important that this state has some very surprising features, of a sort that further erode the once-clear distinction between "something" and "nothing."

In all of the theories I just discussed, the physics of nothing is remarkably rich. Exploring this richness offers insight into the foundations of these theories, in a way that emphasizes some of the most basic ways in which the worlds these theories describe diverge from one another—and in many cases, from our basic intuitions about nature. The physics of nothing boils these theories down to their bare essence, the core of their conceptual structure.

But as I explore in the epilogue, it reveals other things, too.

I suggested above that it is hard to imagine that a region of space with nothing in it could be different from what Newtonian physics tells us it should be. And yet for thousands of years before Newton, empty space was controversial, with many leading philosophers and proto-physicists declaring that the very idea was incoherent. Then, following the success of Newton's theory, the structure of space, time, and matter as understood in Newtonian physics began to be taken for granted—so much so that it became difficult to see how the world could be any other way. But it was precisely this "obvious" conception of empty space that was forced to yield in the face of new theories.

Of course, when our physical theories change, *something* about our conception of nature must change as well. And we should expect the basic principles of our best physics to evolve as we learn more about the world. But the point here is that before general relativity and quantum field theory, it was hard to recognize that there were substantial physical principles at work at all in our understanding of what it would mean to have a region of empty space. The physics of nothing seemed trivial—until we saw that it must be otherwise.

Indeed, according to general relativity and quantum field theory, empty space of the sort Newton imagined is physically *impossible*. Empty space is not merely a stage on which the physics of stuff can unfold; it has structure of its own that is every bit as interesting and complex as the structure of matter. Much of twentieth-century physics has been devoted to understanding just what that structure is.

The real moral of the story I tell in this book is that a crucial part of developing scientific theories is to take basic concepts—concepts like "nothingness"—and make them precise enough to support scientific inquiry. But this process of adapting our intuitive ideas to the more rigorous demands of science can result in radical changes to our conception of reality. And it is often these most basic concepts that are revised when we develop new theories.

The consequences of these sorts of changes are perhaps clearest in the context of the question I asked above. Why is there something rather than nothing? Does modern physics provide an answer to this question after all? In a sense, the answer seems to be "yes": as I just pointed out, modern physics—especially quantum field theory—tells us that nothing, in the sense we would usually have in mind, is impossible.[6] Empty space, at least on one conception, is ruled out by the laws of physics.

But something else is clear as well. How we understand this question and what might count as an answer to it depend on just what we mean by "something" and—perhaps even more—"nothing." You might have thought these terms were somehow unambiguous, independent of our physical theories or our other beliefs about the world. But the physics of nothing shows that this isn't right. How we understand nothingness can vary a great deal.

And this variation is important. How we understand nothingness in general relativity and quantum field theory goes right to the conception of reality that comes with these theories. Nothing really matters. This book tells you why.