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978-1-009-24578-4 — The Cosmic Revolutionary's Handbook
Luke A. Barnes, Geraint F. Lewis
Excerpt
More Information

1 UNDERSTANDING SCIENCE

It is necessary to get behind someone,
before you can stab them in the back.

Sir Humphrey Appleby
Yes, Prime Minister (BBC), 1987

We want to teach you how to overthrow a scientific theory.

That might sound a little "anti-science", but actually you'll be doing scientists a favour. We learn something when bad ideas are exposed. Science often progresses by supporting the reigning ideas, but at other times it has been necessary to storm the castle and install a new monarch. That's how many great scientists rose to fame. *Vive la révolution!*

But you've got to do it right, and that's what this book is about. Revolutions fail for attacking the wrong target, following the wrong tactics, and underestimating the old order. Scientific theories are ideas about the natural world. They claim to know what the universe is like and how it behaves. This tells you how to dethrone a scientific idea: take up the weapon of *observations* and aim squarely at its *predictions*. Show that it can't handle the truth. And be ready with your new monarch when the throne is vacant.

To do all that, you must know your enemy. These wise words from Sun Tzu (or, if you prefer, Rage Against the Machine) are very relevant here: before you can launch a scientific revolution, you need to know the facts, and you need to know the ruling theory and its predictions. Theories aren't installed on the scientific throne by accident, so do your homework.

This book will hand you the facts, point you in the direction of the castle walls, and wish you the very best of luck. In particular, we'll be looking at the biggest scientific target of them all.

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This book is about the universe.

It's about how we observe the universe, either with our naked eyes, or with the many telescopes that now survey the heavens, sensitive to radiation our eyes cannot perceive. But more than that, this book is about how we *understand* the workings of the universe, from its fundamental properties to its largest features. It's about how we put the pieces together.

Current scientific orthodoxy paints a picture of the cosmos that has been built up from many centuries of observation, experimentation, and hard thinking. Great minds throughout scientific history have laid the groundwork, carefully studying the basic rules of motion, space, time, atoms, light, and gravity, to provide the mathematical tools we need to comprehend the changing heavens. Today, *cosmology* – the study of the universe as a whole – is hailed as a paradigm of scientific success.

But what a strange picture! Many find modern cosmology completely unbelievable. The universe, we are told, was born almost 14 billion years ago in a hot and fiery event, cheekily named the *big bang*. At its beginning, everything was compressed into a point of infinite density and infinite temperature. In the aftermath, the universe is *expanding*, but it's not expanding *into* anything. Space itself is stretching.[1] Today, the galaxies we observe in the night sky all appear to be moving away from us. A vast sea of galaxies, stars, and planets fills this expanding space, but because light only moves so fast, most of this universe will be forever beyond the reach of our telescopes, over the *horizon*.

What about the stuff in the universe? Compiling an inventory would appear to be straightforward, if painstaking: just add up all of the stars, planets, and gas clouds that inhabit galaxies and the spaces between the galaxies. But cosmologists say that there is more to the universe than the stuff that we can see. Much, much more. A *dark side* of the universe, which we cannot touch or feel, dominates its energy budget and controls its expansion.

Firstly, modern cosmology tells us that there is *dark matter*. This stuff pervades every galaxy, holding stars in their orbits with its gravitational pull. But dark matter emits no light of its own, and so remains unseen by our telescopes. Stars illuminate the heavens, but dark matter accounts for more than 85% of the mass in the universe. The atoms that make up you and me, stars and planets, are little more than frosting on the cosmic cake.

And then modern cosmology tells us about *dark energy*, a substance as pervasive yet more elusive than dark matter. The case for dark energy was made only in the past few decades. We are told that this substance governs the dynamics of the universe on its largest scales, causing the expansion to accelerate, and driving us towards a cold, dark, dead future.

Why would anyone believe all of that?

A quick internet search turns up plenty of websites, blogs, and videos decrying modern cosmology as wrong, illogical, or even a conspiracy of the scientific establishment that suppresses voices of criticism. Modern cosmology, they claim, is a sham, purposefully distorted and hyped in the hunt for funding. Cosmologists are little more than a self-serving cabal, crushing all opposition.

Maybe, dear reader, you are one of these revolutionary voices, wanting to put science right. Maybe you have ideas about the laws of physics and how they impact our view of stars and galaxies. Maybe you have tried to engage with established astronomers and cosmologists to express your ideas and explain why their view is misguided, but have received a cold shoulder. Why are academics, locked up in their ivory towers, so sure they are right?

Our goal is to explain how physicists, astronomers, and cosmologists developed their picture of how the universe behaves, why they talk about it the way they do, and to tell you what you need to do to confront their strange ideas and begin a revolution. We'll help you build a strategy to battle modern science on a more even playing field, and to ensure that your voice is heard amongst the scientific din.

Just What Is Science?

Warning: the following discussion is very physics-o-centric!

To an outsider, science can be a difficult beast to understand. The media – and especially health advertisements – often tell us

"Science says . . ." and "Scientists have discovered that . . .", but science is not a single, monolithic enterprise. The scientific community consists of many thousands of individuals who often specialize in a narrow set of fields. Some scientists design experiments, some perform observations, and others wrestle with abstract mathematical theories. All spend far too much time in front of a computer. But what is the goal of science?

We begin with an important point: scientists try to predict the future.

If you are not familiar with the workings of science, this might seem a little strange. A flick through popular science magazines such as *New Scientist* or *Scientific American* will reveal stories that focus on *big* scientific questions such as "What is spacetime *really*?" and "What is quantum mechanics *really* telling us about the universe?" But we can't attack these deeper, foundational issues without some help.

In particular, it will help if we can bring these lofty questions down to a practical level. This is the part of science that plays "what if" games, constructing possible physical scenarios and teasing out implications. What if particles of light (*photons*) possessed a tiny amount of mass? What if a cloud of matter collapsed under its own gravity? What if I heat some hydrogen to 10 million degrees? Answering such questions requires more than a vivid imagination: we need our ideas to be translated into the language of mathematics. Sometimes, entirely new mathematical ideas need to be discovered and developed.

The goal of this precision is to connect our ideas to data. Can our new idea account for existing observations of the universe? And, just as importantly, are there any future observations that we could make that would provide further evidence for or against our idea? Can we get one step ahead of nature?

Take gravity as an example. In the 1680s, Isaac Newton published his incredibly successful theory of gravity. With one simple law, he explained how apples fall and how the planets move. Using Newton's law, Edmund Halley was able to predict the future motion of the comet that now bears his name. In 1705, he calculated that it would return in 1758. Sure enough, on Christmas day, it was spotted by a German farmer. Sadly, neither Newton nor Halley was alive to see it.

However, in the mid 1800s, Newton's theory was struggling. Astronomers had discovered that the innermost planet, Mercury, was orbiting slightly out of place, as if pulled by an unseen planet near the Sun. Some even claimed to have observed this newest member of the Solar System, which had been dubbed "Vulcan". Other astronomers, however, could not confirm this sighting. As evidence evaporated and Vulcan consistently failed to turn up where it was predicted to be, this mysterious shortcoming of Newton deepened into a crisis.

In the early 1900s, Einstein proposed his radical new theory of gravity – called the *general theory of relativity* – in which space and time themselves warp, stretch, and wobble. While Einstein's prediction of the orbit of Mercury is only slightly different from that of Newton, that was enough to beautifully align theory with observation. The planet Vulcan was banished to the scientific scrap heap.

Einstein's explanation of Mercury's orbit is impressive, but, like Newton's explanation of the motions of the planets, it comes after the data. We knew about the orbit of Mercury before Einstein proposed his theory. This is sometimes called a "post-diction".

Is there anything wrong with post-diction? We certainly can't discard all the evidence we found before a theory was proposed. Our scientific results would be swayed by something as contingent as what historical order we human beings happened to discover some idea or perform some experiment. That could depend on all sorts of irrelevant factors, like whether Thelma the Theorist took a few days off, or Xavier the Experimenter had a particularly good breakfast.

In principle, prediction and post-diction carry equal weight. But in practice we want to know whether a theory explains the data *naturally*, rather than being glued together from makeshift bits and pieces. Sometimes we can judge this by directly examining the assumptions that underlie the theory. But it is not always easy to tell. Predictions dispel this worry: you can't cook up a theory just to explain data if you don't have the data yet. If a theory correctly predicts the result of an experiment that we haven't done yet, then that is impressive.

So, when a new theory is proposed, we start asking "what if" questions. With Einstein's theory in hand, we have a whole new theoretical universe to explore. We look for new opportunities to test whether these ideas are correct. Einstein predicted that gravity would bend the path of light rays moving near massive objects. Famously, this effect was observed by the British astronomer Sir Arthur Eddington during a solar eclipse in 1919, confirming general relativity's predictions and propelling Einstein to further international fame.

Einstein's theory continues to make successful predictions. In 2015, a hundred years after Einstein's announcement of his new theory, scientists confirmed a hugely important prediction of general relativity: gravitational waves. Space and time can ripple. The discovery of these feeble vibrations, typically swamped by the everyday groans and grumbles of life on Earth, required half a century of effort to build an extraordinarily sensitive detector called the Laser Interferometer Gravitational-Wave Observatory (or LIGO for short). The results were spectacular, with the first signal revealing the merging of two black holes 3 billion years ago in the distant universe. LIGO has opened up a new window on the cosmos.

While Einstein's name is synonymous with scientific genius, you don't need to venture far into the outskirts of the internet to find many people who object to his ideas. Some play the man, rather than the ball, accusing him and the scientific community of outright fraud. Relativity is obviously crazy, they say, but it allows fat-cat scientists to keep feeding off the public purse. Others will decry the "logic" of relativity, often voicing a dislike of the notion of curved space and time, and even accusing the scientific establishment of wilful blindness to their unrecognized genius.

But science holds onto general relativity, not because of hero worship of Einstein, or because we are part of a secret conspiracy. Rather, we use his theory because it works. Physicists dream of proving Einstein wrong; we just haven't been able to do it. We are devising new ways to draw out predictions, and building new experiments to test those predictions.

As we said at the beginning of the chapter, the reigning monarchs of science didn't get there by accident. But they are always vulnerable, because every prediction is a chance to fail. So, what do you need if you want to revolutionize science? A new monarch. You need a model!

Just What Is a Model?

The word *model* has several meanings in the English language, and this can lead to some confusion when talking about a "scientific model". Anarchic comedian Alexei Sayle once said, "my girlfriend's a model. She's an Airfix kit of a Stuka dive bomber!"

We can understand the most important thing about a scientific model by thinking of a model house. Everything in the model is to scale, with one-twentieth size windows, doors, rooms, cupboards, and more. The useful thing about this model is that we can use it to answer questions about the real house. Suppose you want to know whether you can rearrange the living room to incorporate that new sofa you've had your eye on. You can answer this question with the model. If we make a one-twentieth scale model of the new sofa, then we can easily rearrange the model room to see if everything fits. For an accurate model, if the model sofa fits into the model house, then the real sofa would fit into the real house.

This is the crucial feature of a model: using the right translation, we can turn a problem in the real world (will the sofa fit in my living room?) into a problem in the model (will the model sofa fit in the model living room?). We then solve the problem in the model. If the model is an accurate representation of reality, then we have also solved the problem for the real world.

In the case of a model house, the translation between the model and reality is simple: it's just 20 times smaller. For a scientific model, the mathematical framework can be more complicated, but the crucial feature is the same: we can translate a question about the real world into a question about the model. Because we can relate between the two, we can make predictions. We can ask questions such as “what if I performed such-and-such experiment?”

Let’s take another look at Newton’s model for gravity. (We’re physicists. We like Newton!) We can express his idea in words: gravity will produce a force between two masses, whose magnitude is proportional to the product of the two masses, and inversely proportional to the square of the distance between the masses. That’s interesting, but not much use to a working scientist. To a scientist, the useful form of Newton’s law of gravity looks like this:

$$\vec{F} = -G\frac{M_1 M_2}{r^2}\,\hat{r}$$

If you are not a fan of mathematics, and if this equation looks like little more than gobbledygook, don’t worry too much. We can look at this like a machine, where we input two values for the masses, M_1 and M_2, and the distance between them, r, and this machine returns the gravitational force between them. The other number in the equation is G, which is known as Newton’s gravitational constant. It scales the numbers so the result has the correct unit (which, for force, is the *newton*). Finally, $\hat{r}$ (“r” with a little hat) is known as a *unit vector*; it tells you that the force pulls the masses towards each other. But what can you do with this bit of mathematics?

We turn to Newton’s laws of motion. We can state the idea in words as “forces cause objects to change their speed and direction of travel”. But as we have noted, it’s the mathematical version of the law that allows us to make precise predictions:

$$\vec{F} = m\,\vec{a}$$

This equation might be familiar from high-school physics; F is the force, a is the acceleration, and m is the mass. Combining these equations, we can start with information about the position and velocity (which encodes speed and direction) of the objects in the system at a particular time, and transform it into a prediction about the future of the system. For example, if we know where all the Solar System's planets are today, and how fast and in what direction they are moving, we can calculate where they will be at any future time.

The point of all physical models – Newton's, Einstein's, and anyone else's – is that we can ask questions about the universe. Given where I saw the planet Mercury last night, where will I see it tonight? By how much will the path of a light ray bend as it passes close to the Sun? We can ask Newton's model, and we can ask Einstein's model, and then we can actually look at the universe to see if either is correct.

The lesson is that if you are going to revolutionize science, you need a mathematical model. Words will not do. As scientists, we regularly get emails and letters espousing new ideas about the cosmos, from theories about fundamental particles to new interpretations of galaxy redshifts and the expansion of the universe. Surprisingly often, the author confesses that they are unable to express these ideas mathematically. I'm sure my idea is correct, they say, I just need some help working out the mathematics. To a scientist, and particularly to a physicist, this is a bit like saying "I have a great idea for a symphony; I just need some help with the musical notes" or "I'm sure I could do brain surgery; I just need some pointers on where to start cutting."

For a physicist, you don't really *have* a theory until you can think about it clearly enough to put it in mathematical form. Without precise predictions, it is too easy to fool yourself into thinking that the data is consistent with your idea. We need to predict measurements and observations, so that we can hold this mathematical model up to nature.[2]

What Makes a *Good* Scientific Model?

What does a scientist want in a scientific model? We have emphasized that your model must present a precise, quantitative picture of the universe, one that allows us to predict the results of experiments. But this is not the only criterion that scientists use. Historians and philosophers of science, by studying how scientists actually argue for and against theories, have proposed sets of *theoretical virtues*, that is, traits of a good scientific idea.

Not everyone agrees about all of the virtues, of course, but there is a common core that scientists will recognize. We will look at a recent list of twelve theoretical values (TVs) compiled by historian Mike Keas.[3] His list is helpfully comprehensive: while the twelve values overlap somewhat, each pinpoints something important about good scientific theories.

The first three relate to how your theory handles the evidence.

TV1. Evidential accuracy: your theory accounts for or fits the data well.

TV2. Causal adequacy: your theory posits causes that account for the effects we see in the data.

TV3. Explanatory depth: your theory applies to a wide range of scenarios.

Clearly, if your theory is correct, or at least approximately correct, then it should explain the data (TV1). All the data! Cherry-picking – focusing on the results that your mathematical model can describe, while ignoring those where it fails – is a scientific sin. This is a sure road to being ignored by the scientific community.

But scientists want more from a theory than this. The theory that the continents can move over the surface of the Earth explains why they appear to fit together like a jigsaw puzzle. But when it was first proposed, this theory was rightly criticized because it lacked causal adequacy (TV2): it didn't tell us *how* the continents moved. Frankly, no one had much of an idea of how something as large as a continent *could* slide around the Earth's surface. The theory of plate tectonics added the all-important details.

But the theory of plate tectonics does even more. It has implications for a wide range of facts about the Earth's surface: how mountains form, how lava comes to the surface in volcanos, and the origin of earthquakes along fault lines. Scientists prefer broad theories that explain a lot about the universe (TV3).