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FAREWELL TO REALITY

HOW MODERN PHYSICS HAS BETRAYED THE SEARCH FOR SCIENTIFIC TRUTH

JIM BAGGOTT

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To John, in memory of Mary

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Preface

Modern physics is heady stuff. It seems that we can barely get through a week without being assaulted by the latest astounding physics story, its headlines splashed gaudily across the covers of popular science magazines and, occasionally, newspapers. The public's appetite for these stories is seemingly insatiable, and there's no escaping them. They are the subjects of innumerable radio and television news reports and documentaries, the latter often delivered with breathless exuberance and lots of arm-waving, from unconnected but always exotic locations, against a background of overly dramatic music.[*]

We might agree that these stories are all very interesting and entertaining. *But are they true?*

What evidence do we have for super-symmetric 'squarks', or superstrings vibrating in a multidimensional spacetime? How can we tell that we live in a multiverse? Is it really the case that the fundamental constituent at the heart of all matter and radiation is just 'information'? How can we tell that the universe is a hologram projected from information encoded on its boundary? What are we really supposed to make of the intricate network of apparent cosmic coincidences in the laws of physics?

Now, modern science has discovered that the reality of our physical existence is bizarre in many ways, but this is bizarreness for which there is an accumulated body of accepted scientific evidence. There is as yet *no* observational or experimental evidence for many of the concepts of contemporary theoretical physics, such as super-symmetric particles, superstrings, the multiverse, the universe as information, the holographic principle or the anthropic cosmological principle. For some of the wilder speculations of the theorists there can by definition *never* be any such evidence.

This stuff is not only not true, it is not even science. I call it 'fairytale physics'.[*] It is arguably borderline confidence-trickery.

Matters came to a head for me personally one evening in January 2011. That evening the BBC broadcast an edition of its flagship *Horizon* science series, entitled 'What is Reality?'. This began quite reasonably, with segments on the discovery of the top quark at Fermilab and some of the more puzzling conclusions of quantum theory. But beyond this opening the programme went downhill. It became a showcase for fairy-tale physics.

There was no acknowledgement that this was physics that had long ago lost its grip on anything we might regard as descriptive or explicative of the real world we experience. *Horizon* has an impressive reputation, and I became deeply worried that many viewers might be accepting what they were being told at face value. Conscious that I was now shouting rather pointlessly at my television, I decided that it was time to make a stand.

But, you might ask, what's the big deal? Why get so worked up? After all, consumers of popular science may simply wish to be entertained. They may wish to have their already boggled minds further boggled by the latest 'scientific' thinking, through a rapid succession of 'Oh wow!' revelations. Blimey! Parallel universes!

To take this view is, I believe, greatly to underestimate the people who consume popular science. It also shows an astonishing lack of respect. I suspect that many people might actually like to know what is accepted science fact and what is science fantasy. Only the hard facts can illuminate the situation sufficiently to make it possible to judge the nature of the trick, and to decide if it involves a betrayal of confidence, or even a betrayal of the truth.

Put it this way. If we were to regard fairy-tale physics as a lively branch of contemporary philosophy rather than science, do you think it would continue to receive the same level of attention from funding agencies, universities, popular science publishers, the producers of radio and television programmes and the wider public? No?

This is the big deal.

In writing this book, I've tried to hold on to several ambitions. I wanted to describe what modern physics has to say about the nature of our physical reality, based as far as possible on the accepted body of observationally or experimentally grounded scientific fact.

But we have to accept that even in this 'official' or 'authorized' version of reality there are many grey areas, where we run out of hard facts and have to deal with half-truths, guesses, maybes and a little imaginative speculation. This description is the nearest we can get to reality given the current gaps in our knowledge.

I also wanted to convince you that whilst the knowledge in this authorized version goes very deep, it does seem that we have paid a high price for it. We now know much more about the physical world than we have done at any other time in history. But I believe that we comprehend and understand much less.

We were obliged to abandon Isaac Newton's clockwork universe quite some time ago, but there was an inherent comprehensibility about this description that we found familiar and maybe even comforting (unless you happened to be a philosopher). The world according to quantum theory remains distinctly unfamiliar and uncomfortable. 'Nobody understands quantum mechanics,' declared the charismatic American physicist and Nobel laureate Richard Feynman, with some justification.[*] And today, more than a hundred years after it was first discovered, the theory remains completely inscrutable.

Some modern theoretical physicists have sought to compensate for this loss of understanding. Others have tried to paper over the cracks in theories that are clearly not up to the task. Or they have pushed, with vaulting ambition, for a final 'theory of everything'. These physicists have been led — unwittingly or otherwise — to myth creation and fairy tales.

I want to be fair to them. These physicists have been wrestling with problems for which there are as yet no observational or experimental clues to help guide them towards solutions. They are problem-rich, but data-poor. Rather than simply pleading ignorance or focusing their efforts on more tractable problems, they have chosen instead to abandon the obligation to refer their theories to our experience of the real world. They have chosen to abandon the scientific method.

In doing this, some theorists have railed against the constraints imposed by a scientific methodology that, they argue, has outlived its usefulness. They have declared that the time has come to embrace a new methodology for a 'post-empirical science'.

Or, if you prefer, they have given up.

With no observational or experimental data to ground their theories in reality, these theorists have been guided instead by their mathematics and their aesthetic sensibilities. Not surprisingly, ever more outrageous theoretical speculations freed from the need to relate to things happening in the world that we experience have transported us to the far wild shores of the utterly incredible and downright ridiculous.

This is not a wholly new phenomenon. Speculative theorising has always played an important role in scientific development, and in this book we will take a look at some examples from history. However, under the stark, unyielding gaze of the scientific method, in the light of new observational or experimental data such speculations have either become absorbed into mainstream science or they have fallen by the wayside and been rigorously forgotten.

But contemporary theoretical physics seems to have crossed an important threshold in at least two senses. Speculative theorizing of a kind that cannot be tested, that cannot be verified or falsified, a kind that is not subject to the mercilessness of the scientific method, is now almost common currency. The discipline has retreated into its own small, self-referential world. Its product is traded by its advocates as mainstream science within the scientific community, and peddled (or even missold) as such to the wider public.

Secondly, the unprecedented appetite for popular science and its attraction as an income stream have proved hard for the more articulate and eloquent of these advocates to resist. The result is that virtually every other popular book published on aspects of modern physics is chock-full of fairy stories. It is pseudo-science masquerading as science.

This will prove to be a controversial book. I'm not hopelessly naive — I don't expect it to change current thinking or current practices. But I am hopeful that it will provoke some debate and, at the very least, provide a timely and much-needed antidote.[*]

In August 2011, I joined popular science writer Michael Brooks in a discussion about science at the Edinburgh International Book Festival. Brooks encouraged the assembled audience to imagine who members of the general public would name if asked to identify three scientists. He went on to suggest Albert Einstein, Stephen

Hawking and Brian Cox.[**] The last is a former pop star turned high-energy physicist and television science presenter who has rapidly established himself as an important UK media personality. Interestingly, all are (or were) physicists.

The contrasting approaches of Einstein and Hawking are particularly relevant to the aims of this book. Hawking is a rather indulgent fairytale physicist, recently declaring that a form of untried and untested (and possibly untestable) superstring theory is the unified theory that Einstein spent the latter part of his life searching for.

Einstein, in contrast, was a theoretical physicist of the old school. His many pronouncements on the aims of science and the methods that scientists use are broadly consistent with common conception among both the majority of scientists and the wider public. On the basis of these pronouncements I suspect he would have been quite shocked by the state of contemporary theoretical physics. I had initially thought to title this book *What Would Einstein Say?* but have settled for trying to convey his likely sense of outrage by identifying for each chapter relevant quotations from his extraordinary lexicon.

I am no longer a professional scientist, and some might argue that this means I am no longer qualified to hold an opinion on this subject. Obviously, I don't agree. I believe I have studied it long and hard enough to allow me not only to form and hold an opinion but also to express it as best I can.

But make no mistake, what you have in this book is an opinion that is very *personal*. Consequently, when I acknowledge a debt of gratitude to Professors Steve Blundell at Oxford University, Helge Kragh at Aarhus University in Denmark and Peter Woit at Columbia University in New York, who read and commented on the draft manuscript, I want to be absolutely clear that this acknowledgement should not suggest that they accept all my arguments. Of course, I take full responsibility for any errors or misconceptions that remain.

Jim Baggott
July 2012

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[*] And, to my mind at least, produced for an audience of 12 year olds suffering from attention deficit disorder. Or maybe I'm just getting too old and cranky? Answers on a postcard please …

[*] With acknowledgement to Piers Bizony.

[*] This quote appears in Richard Feynman, *The Character of Physical Law*, (MIT Press, Cambridge, MA, 1965), p. 129

[*] And yes, I'm also interested in the income-stream.

[**] My daughter, shortly to start her second year as a university drama student, was sitting dutifully in the audience. She thought about Brooks' question and challenged herself to name three scientists. Before Brooks could continue, she had identified Einstein, Hawking and Cox.

1

The Supreme Task

Reality, Truth and the Scientific Method

The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction. There is no logical path to these laws; only intuition, resting on sympathetic understanding of experience, can reach them.

Albert Einstein[1]

Now I want to be absolutely clear and unequivocal upfront. I trained as a scientist, and although I no longer practise, I continue to believe — deeply and sincerely — that only science, correctly applied, can provide a sure path to true knowledge of the real world. If you want to know what the world is made of, where it came from, how it works and how it came to be as it is today, then my recommendation is to look to science for the answers.

I hope I speak with conviction, but be assured that I am not a zealot. I will happily admit that the practice of science is not always black and white. We are forced to admit shades of grey. It is a lot looser and more ambiguous than many practitioners are themselves often willing to admit. Much of the looseness and ambiguity arises because science is after all a human endeavour, and human beings are complicated and unpredictable things.

But it would be a mistake to think that the humanity of scientists is responsible for all the vagueness, that everything would be crystal clear if only a few flaky individuals would stick to the rules. When we look closely, we discover that what passes for the 'rules' of scientific endeavour are themselves rather vague and open to interpretation. This, I will argue, is how fairy-tale physics manages to thrive.

Our problems begin as soon as we try to unpack the sentences that I used to open this introductory chapter. Reality is at heart a metaphysical concept — it is, quite simply, 'beyond physics' and therefore beyond science. And just what, exactly, is this thing we call 'science'? For that matter, how should we define 'truth'?

That's a lot of difficult questions. And, it seems, if I'm going to accuse a bunch of theoretical physicists of abandoning the scientific method and so betraying the search for scientific truth about the nature of physical reality, then I'll need properly to ground this assertion in some definitions. It's better to try to clear all this up before we really get going.

There's quite a lot at stake here, so I've summarized my main conclusions about reality, science and truth in a series of six 'principles', handily picked out in italics with a grey background so that you can easily refer back to them if needed. Collectively, these principles define what it is that we apply science to, what science is and how we think we know when it is 'true'.

Of course, many physicists and philosophers of science will disagree with these principles, with varying degrees of vehemence. This, I think, is rather the point. What's important is how they seem to *you*.

In Part I, my mission will be to tell the story of the authorized version of reality in the context of these statements, showing how science has been applied to generate this contemporary version of the truth. This section concludes with a chapter summarizing most (but not all) of the problems with this authorized version and gives the reasons why we know it can't be the whole truth.

In Part II, I will attempt to explain how contemporary theoretical physics seeks to address these problems. It is here that fairy-tale physics sneaks in through unavoidable loopholes in our interpretation of one or more of the principles, but fails to satisfy all of them taken together. It is on this basis that I will seek to reject fairy-tale physics as metaphysics.

Let's start with reality.

Real is simply electrical signals interpreted by your brain

'What is real?' asked the character Morpheus in the 1999 Hollywood blockbuster movie *The Matrix*. 'How do you define real? If you're talking about what you can feel, what you can smell, what you can taste and see, then real is simply electrical signals interpreted by your brain.'[2]

These days we tend not to look for profundity in a Hollywood movie,[*] but it's worth pausing for a moment to reflect on this observation. I want to persuade you that reality is like liquid mercury: no matter how hard you try, you can never nail it down. I propose to explain why this is by reference to three 'everyday' things: a red rose, a bat and a dark cave.

So, imagine a red rose, lying on an expanse of pure white silk. We might regard the rose as a thing of beauty, its redness stark against the silk sheen of brilliant nothingness. What, then, creates this vision, this evocative image, this tantalizing reality? More specifically, what in reality creates this wonderful experience of the colour red?

That's easy. We google 'red rose pigment' and discover that roses are red because their petals contain a subtle mixture of chemicals called anthocyanins, their colour enhanced if grown in soil of modest acidity. So, anthocyanins in the rose petals interact with sunlight, absorbing certain wavelengths of the light and reflecting predominantly red light into our eyes. We look at the petals and we see red. This all seems quite straightforward.

But hang on. What, precisely, is 'red light'? Our instinct might be to give a scientific answer. Red light is electromagnetic radiation with wavelengths between about 620 and 750 billionths of a metre. It sits at the long-wavelength end of the visible spectrum, sandwiched between invisible infrared and orange.

But light is, well, light. It consists of tiny particles of energy which we call photons. And no matter how hard we look, we will not find an inherent property of 'redness' in photons with this range of wavelengths. Aside from differences in wavelength, there is nothing in the physical properties of photons to distinguish red from green or any other colour.

We can keep going. We can trace the chemical and physical changes that result from the interactions of photons with cone cells in your retina all the way to the stimulation of your visual cortex at the back of your brain. Look all you like, but you will not find the *experience* of the colour red in any of this chemistry and physics. It is obviously only when you synthesize the information being processed by your visual cortex in your *conscious mind* that you experience the sensation of a beautiful red rose. And this is the point that Morpheus was making.

We could invent some equivalent scenarios for all of our other human senses — taste, smell, touch and hearing. But we would come to much the same conclusion. What you take to be your reality is just electrical signals interpreted by your brain.

What is it like to be a bat?

Now, you might be ready to dismiss all this as just so much juvenile philosophizing. Of course we're all reliant on the way our minds process the information delivered to us by our senses. But does it make any sense at all for the human mind to have evolved processes that represent reality differently from how it really is? Surely what we experience and the way we experience it *must* correspond to whatever it is that's 'out there' in reality? Otherwise how could we survive?

To answer these questions, it helps to imagine what it might be like to be a bat.

What does the world look like — what passes for reality — from a bat's point of view? We know that bats compensate for their poor night vision by using sophisticated sonar, or echolocation. Bats emit high-frequency sounds, most of them way above the threshold of human perception. These sound waves bounce off objects around them, forming echoes which they then detect.

Human beings do not use echolocation to gather information about the world. We cannot possibly imagine what it's like for a bat to be a bat because we lack the bat's sensory apparatus, in much the same way that we cannot begin to describe colours to someone who has been blind from birth.

But the bat is a highly evolved mammal, successful in its own ecological niche. Just because I can't understand what reality might be like for a bat doesn't mean that the bat's perceptions and experiences of that reality are any less legitimate than mine.

What this suggests is that evolutionary selection pressures lead to the development of a sensory apparatus that delivers a finely tuned *representation* of reality. All that matters is that this is a representation that lends a creature survival advantages. There is no evolutionary selection pressure to develop a mind to represent reality as it really is.

Plato's allegory of the cave

So, what do we perceive if not reality as it really is? In *The Republic*, the ancient Greek philosopher Plato used an allegory to describe the situation we find ourselves in. This is his famous allegory of the cave.

Imagine you are a prisoner in a dark cave. You have been a prisoner all your life, shackled to a wall. You have never experienced the world outside the cave. You have never seen sunlight. In fact, you have no knowledge of a world outside your immediate environment and are not even aware that you are a prisoner, or that you are being held in a cave.

It is dark in the cave, but you can nevertheless see men and women passing along the wall in front of you, carrying all sorts of vessels, and statues and figures of animals. Some are talking. As far as you are concerned, the cave and the men and women you can see constitute your reality. This is all you have ever known.

Unknown to you, however, there is a fire constantly burning at the back of the cave, filling it with a dim light. The men and women you can see against the wall are in fact merely shadows cast by real people passing in front of the fire. The world you perceive is a world of crude appearances of objects which you have mistaken for the objects themselves.

Plato's allegory was intended to show that whilst our reality is derived from 'things-in-themselves' — the real people that walk in front of the fire — we can only ever perceive 'things-as-they-appear' — the shadows they cast on the cave wall. We can never perceive reality for what it is; we can only ever perceive the shadows. *'Esse est percipi',* declared the eighteenth-century Irish philosopher George Berkeley: essence is perception, or to be is to be perceived.

These kinds of arguments appear to link our ability to gain knowledge of our external reality firmly with the workings of the human mind. A disconnect arises because of the apparent unbridgeable distance between the physical world of things and the ways in which our perception of this shapes our mental world of thoughts, images and ideas. This disconnect may arise because we lack a rigorous understanding of how the mind works. But knowing how the mind works wouldn't change the simple fact that thoughts are very different from things.

Veiled reality

It doesn't end here. Another disconnect, of a very different kind but no less profound, is that between the quantum world of atomic and subatomic dimensions and the classical world of everyday experience. What we will discover is that our anxiety over the relationship between reality and perception is extended to that between reality and measurement.

Irrespective of what thoughts we think and how we think them, we find that we can no longer assume that what we *measure* necessarily reflects reality as it really is. We discover that there is also a difference between 'things-in-themselves' and 'things-as-they-are-measured'.

The contemporary physicist and philosopher Bernard d'Espagnat called it 'veiled reality', and commented that:

> … we must conclude that physical realism is an 'ideal' from which we remain distant. Indeed, a comparison with conditions that ruled in the past suggests that we are a great deal more distant from it than our predecessors thought they were a century ago.[3]

At this point the pragmatists among us shrug their shoulders and declare: 'So what?' I can never be sure that the world as I perceive or measure it is really how the world is 'in reality', but this doesn't stop me from making observations, doing experiments and forming theories about it. I can still establish facts about the shadows — the projections of reality into our world of perception and measurement — and I can compare these with similar facts derived by others. If these facts agree, then surely we have learned something about the nature of the reality that lies beneath the shadows. We can still determine that if we do *this,* then *that* will happen.

Just because I can't perceive or measure reality as it really is doesn't mean that reality has ceased to exist. As American science-fiction writer Philip K. Dick once observed: 'Reality is that which, when you stop believing in it, doesn't go away.'[4]

And this is indeed the bargain we make. Although we don't always openly acknowledge it upfront, 'reality-in-itself' is a metaphysical concept. The reality that we attempt to study is inherently an *empirical reality* deduced from our studies of the shadows. It is the reality of observation, measurement and perception, of things-as-they-appear and of things-as-they-are-measured. As German physicist Werner Heisenberg once claimed: '… we have to remember that what we observe is not nature in itself but nature exposed to our method of questioning'.[5]

But this isn't enough, is it? We may have undermined our own confidence that there is anything we can ever know about reality-in-itself, but we must still have some *rules.* Whatever reality-in-itself is really like, we know that it must exist. What's more, it must surely exist independently of perception or measurement. We expect that the shadows would continue to be cast whether or not there were any prisoners in the cave to observe them.

We might also agree that, whatever reality is, it does seem to be rational and predictable, within recognized limits. Reality appears to be logically consistent. The shadows that we perceive and measure are not completely independent of the things-in-themselves that cause them. Even though we can never have knowledge of the things-in-themselves, we can *assume* that the properties and behaviour of the shadows they cast are somehow determined by the things that cast them.

That feels better. It's good to establish a few rules. But don't look too closely. If you want some assurance that there are good, solid scientific reasons for believing in the existence of an independent reality, a reality that is logical and structured, for which our cause-and-effect assumptions are valid, then you're likely to be disappointed. To repeat one last time, reality is a metaphysical concept — it lies beyond the grasp of science. When we adopt specific beliefs about reality, what we are actually doing is adopting a specific *philosophical position.*

If we accept the rules as outlined above, then we're declaring ourselves as *scientific realists.* We're in good company. Einstein was a realist, and when asked to justify this position he replied: 'I have no better expression than the term "religious" for this trust in the rational character of reality and in its being accessible, to some extent, to human reason.'[6]

Now, it's one thing to be confident about the existence of an independent reality, but it's quite another to be confident about the existence of overtly theoretical entities that we might want to believe to exist in some shape or form within this reality. When we invoke entities that we can't directly perceive, such as photons or electrons, we learn to appreciate that we can't know anything of these entities as things-in-themselves. We may nevertheless choose to assume that they exist. I can find no better argument for such ‘entity realism’ than a famous quote from philosopher Ian Hacking’s book *Representing and Intervening*. In an early passage in this book, Hacking explains the details of a series of experiments designed to discover if it is possible to reveal the fractional electric charges characteristic of ‘free’ quarks.[*] The experiments involved studying the flow of electric charge across the surface of balls of superconducting niobium:

> Now how does one alter the charge on the niobium ball? ‘Well, at that stage,’ said my friend, ‘we spray it with positrons to increase the charge or with electrons to decrease the charge.’ From that day forth I’ve been a scientific realist. *So far as I’m concerned, if you can spray them then they are real.*[7]

This brings us to our first principle.

> **The Reality Principle.** *Reality is a metaphysical concept, and as such it is beyond the reach of science. Reality consists of things-in-themselves of which we can never hope to gain knowledge. Instead, we have to content ourselves with knowledge of empirical reality, of things-as-they-appear or things-as-they-are-measured. Nevertheless, scientific realists assume that reality (and its entities) exists objectively and independently of perception or measurement. They believe that reality is rational, predictable and accessible to human reason.*

Having established what we can and can’t know about reality, it’s time to turn our attention properly to science.

The scientific method

In 2009, Britain’s Science Council announced that after a year of deliberations, it had come up with a definition of science, perhaps the first such definition ever published: ‘Science is the pursuit of knowledge and understanding of the natural and social world following a systematic methodology based on evidence.’[8]

Given that any simple definition of science is likely to leave much more unsaid than it actually says, I don’t think this is a bad attempt. It all seems perfectly reasonable. There’s just the small matter of the ‘systematic methodology’, the cold, hard, inhuman, unemotional logic engine that is supposed to lie at the very heart of science. A logic that we might associate with Star Trek’s Spock.

The ‘scientific method’ has at least three components. The first concerns the processes or methodologies that scientists use to establish the hard facts about empirical reality. The second concerns methods that scientists use to create abstract theories to accommodate and explain these facts and make testable predictions. The third concerns the methods by which those theories are tested and accepted as true or rejected as false. Let’s take a look at each of these in turn.

Getting at the facts

The first component seems reasonably straightforward and should not detain us unduly. Scientists pride themselves on their detachment and rigour. They are constantly on the lookout for false positives, systematic errors, sample contamination, anything that might mislead them into reporting empirical facts about the world that are later shown to be wrong.

But scientists are human. They are often selective with their data, choosing to ignore inconvenient facts that don't fit, through the application of a range of approaches that, depending on the circumstances, we might forgive as good judgement or condemn as downright fraud. They make mistakes. Sometimes, driven by greed or venal ambition, they might cheat or lie.

There is no equivalent of a Hippocratic oath for scientists, no verbal or written covenant to commit them to a system of ethics and work solely for the benefit of humankind. Nevertheless, ethical behaviour is deeply woven into the fabric of the scientist's culture. And the emphasis on repetition, verification and critical analysis of scientific data means that any mistakes or wrongdoing will be quickly found out.

Here's a relevant example from contemporary high-energy physics. The search for the Higgs boson at CERN's Large Hadron Collider has involved the detection and analysis of the debris from trillions upon trillions of protons colliding with each other at energies of seven and, most recently, eight trillion electron volts.[*] If the Higgs boson exists, then one of the many ways in which it can decay involves the production of two high-energy photons, a process written as $H \rightarrow \gamma\gamma$, where H represents the Higgs boson and the Greek symbol γ (gamma) represents a photon.

About three thousand physicists have been involved in each of two detector collaborations searching for the Higgs, called ATLAS and CMS.[**] One of their tasks is to sift through the data and identify instances where the proton—proton collisions have resulted in the production of two high-energy photons. They narrow down the search by looking for photons emitted in specific directions with specific energies. Even so, finding the photons can't be taken as evidence that they come from a Higgs boson, as theory predicts that there are many other ways in which such photons can be produced.

The physicists therefore have to use theory to calculate the 'background' events that contribute to the signal coming from the two photons. If this can be done reliably, and if any systematic errors in the detectors themselves can be estimated or eliminated, then any significant excess events can be taken as evidence for the Higgs.

On 21 April 2011, an internal discussion note from within the ATLAS collaboration was leaked to a high-energy physics blogger. The note suggested that clear evidence for a Higgs boson had been found in the $H \rightarrow \gamma\gamma$ decay channel, with a signal thirty times greater than predicted.

If this was true, it was fantastic, if puzzling, news. But it wasn't true. The purpose of internal discussion notes such as this is to allow the exchange of data and analysis within the collaboration before a collective, considered view is made public. It was unfortunate that the note had been leaked. Within just a few weeks, ATLAS released an official update based on the analysis of twice as much collision data as the original note, work that no doubt demanded many more sleepless nights for those involved. There was no excess of events. No Higgs boson — yet.[*]

As ATLAS physicist Jon Butterworth subsequently explained:

> Retaining a detached scientific approach is sometimes difficult. And if we can't always keep clear heads ourselves, it's not surprising people outside get excited too. This is why we have internal scrutiny, separate teams working on the same analysis, external peer review, repeat experiments, and so on.[9]

This was a rare example in which the public got to see the way science self-regulates, how it uses checks and balances in an attempt to ensure that it gets its facts right. Scientists don't really like us looking over their shoulders in this way, as they fear that if we really knew what went on, this would somehow undermine their credibility and authority.

I take a different view. The knowledge that science can be profoundly messy on occasion simply makes it more human and accessible; more Kirk than Spock. Knowing what can go wrong helps us to appreciate that when it does go seriously wrong, this is usually an exception, rather than the rule.

No facts without theory

The process of building a body of accepted scientific facts is often fraught with difficulty, and rarely runs smoothly. We might be tempted to think that once we have built it, this body of evidence forms a clear, neutral, unambiguous substrate on which scientific theories can be contrived. Surely the facts form a 'blank sheet of paper', on which the theorists can exercise their creativity?

But this is not the case. It is in fact impossible to make an observation or perform an experiment without the context of a supporting theory in some shape or form. French physicist and philosopher Pierre Duhem once suggested that we go into a laboratory and ask a scientist performing some basic experiments on electrical conductivity to explain what he is doing:

> Is he going to answer: 'I am studying the oscillations of the piece of iron carrying this mirror?' No, he will tell you that he is measuring the electrical resistance of a coil. If you are astonished, and ask him what meaning these words have, and what relation they have to the phenomena he has perceived and which you at the same time perceived, he will reply that your question would require some long explanations, and he will recommend that you take a course in electricity.[10]

Facts are never theory-neutral; they are never free of contamination from some theory or other. As we construct layer upon layer of theoretical understanding of phenomena, the concepts of our theories become absorbed into the language we use to describe the phenomena themselves. Facts and theory become hopelessly entangled.

If you doubt this, just look back over the previous paragraphs concerning the search for the Higgs boson at CERN.

This brings us to our second principle.

> **The Fact Principle**. *Our knowledge and understanding of empirical reality are founded on verified scientific facts derived from careful observation and experiment. But the facts themselves are not theory-neutral. Observation and experiment are simply not possible without reference to a supporting theory of some kind.*

So how do scientists turn this hard-won body of evidence into a scientific theory?

Theory from facts: anything goes?

The naïve answer is to say that theories are derived through a process of *induction.* Scientists use the data to evolve a system of generalizations, built on abstract concepts.

The generalizations may be elevated to the status of natural patterns or 'laws'. The laws in turn are explained as the logical and inevitable result of the properties and behaviour of a system of theoretical concepts and theoretical entities.

A suitable example appears to be provided by the German mathematician and astronomer Johannes Kepler, who deduced his three laws of planetary motion after years spent mulling over astronomical data collected by the eccentric Dane Tycho Brahe, at Benatky Castle and Observatory near Prague.

Brahe's painstaking observations of the motion of the planet Mars suggested a circular orbit around the sun, to within an accuracy of about eight minutes of arc. But this was not good enough for Kepler:

> … if I had believed that we could ignore these eight minutes, I would have patched up my hypothesis accordingly. But since it was not permissible to ignore them, those eight minutes point the road to a complete reformulation of astronomy.[11]

Brahe's observations were just too good.

In his book *Astronomia Nova (New Astronomy)*, published in 1609, Kepler used Brahe's data to argue that the planets move not in circular orbits around the sun, but in elliptical orbits with the sun at one focus. For this scheme to work, he had to assume that the earth behaves like just any other planet, also moving around the sun in an orbit described by an ellipse.[*]

This means that a planet moves closer to the sun for some parts of its orbit and further away for other parts. Kepler also noted a balance between the distance of the planet from the sun and the speed of its motion in the orbit. A planet moves faster around that part of its orbit that takes it closest to the sun, and more slowly in that part of its orbit that is more distant. An imaginary line drawn from the sun to the planet will sweep out an area as the planet moves in its orbit. Kepler deduced that the balance between speed and proximity to the sun means that no matter where the planet is in its orbit, such an imaginary line will sweep out equal areas in equal times.

In 1618, Kepler added a third law. The cube of the mean radius of the orbit divided by the square of the period (the time taken for a planet to complete one trip around the sun) is approximately constant for all the planets in the solar system.

Kepler had used Brahe's facts to develop a set of empirical laws based on the abstract concept of an elliptical orbit. In 1687, Isaac Newton deepened our understanding by devising a theory that explained the origins of Kepler's elliptical orbits in terms of other abstract concepts — the forces acting between bodies — in three laws of motion and a law of universal gravitation.

So, this seems all very straightforward. Kepler induced his three laws from Brahe's extensive set of accurate astronomical data. Newton then 'stood on the shoulders of giants', using Kepler's conclusions, among many others, to derive his own laws, thus driving science inexorably in the direction of ultimate truth. Right?

Wrong. Whenever historians examine the details of scientific discoveries, they inevitably find only confusion and muddle, vagueness and error, good fortune often pointing the way to the right answers for the wrong reasons. Occasionally they find true genius. Theorizing involves a deeply human act of creativity. And this, like humour, doesn't fare well under any kind of rational analysis.