JIM BAGGOTT

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LOOP QUANTUM GRAVITY AND THE SEARCH FOR THE STRUCTURE OF SPACE, TIME, AND THE UNIVERSE

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PREFACE

Let's get one thing straight.

This is a book about loop quantum gravity, one of several contemporary approaches to the development of a quantum theory of gravity, perched right on the very edge of our current understanding of space, time, and the physical universe. One hopes that science at the frontiers will always make for entertaining reading but, make no mistake, like all such theories, as of today there is *not one single piece of observational or experimental evidence to support it.*[1]

You might then wonder why I think you ought to be interested in this.

Here's why. There's little doubting that in these first few decades of the twenty-first century we face some tremendous economic, political, and environmental challenges, some much more stubborn and intractable than others. But when it comes to our ability to comprehend the nature of space and time, to understand the very fabric of physical reality, *the quantum theory of gravity is simply the greatest scientific problem of our age.*[2] It addresses the ultimate 'big question' of existence. Resolving this problem demands a real depth of scientific expertise; it demands unique moments of insight and inspiration; and it demands intellectual creativity likely to be unsurpassed in the entire history of physics.

The reason is simple. Today we are blessed with two extraordinarily successful theories. The first is Albert Einstein's general theory of relativity, which describes the large-scale behaviour of matter in a curved spacetime. It tells us how *gravity* works: matter tells spacetime how to curve, and curved spacetime tells matter how to move. This theory is the basis for the so-called standard model of Big Bang cosmology. We use it to describe the evolution of our universe from almost the very 'beginning', which on current evidence happened about 13.8 billion years ago. The discovery of gravitational waves at the LIGO observatory in the USA (and now Virgo, in Italy) is only the most recent of this theory's many triumphs.

The second is quantum mechanics. This theory describes the properties and behaviour of matter and radiation at its smallest scales; at the level of molecules, atoms, sub-atomic, and sub-nuclear particles. In the guise of quantum field theory it is the basis for the so-called standard model of particle physics, which builds up all the visible constituents of the universe (including stars, planets, and us) out of collections of quarks, electrons, and force-carrying particles such as photons. It tells us how the other three forces of nature work: electromagnetism, the strong force, and the weak interaction. The discovery of the Higgs boson at CERN in Geneva is only the most recent of this theory's many triumphs.

But, while they are both highly successful, grand intellectual achievements, these two standard models are also riddled with holes. There's an awful lot they can't explain, and they leave a lot of important questions unanswered. If anything, their successes have only served to make the universe appear more elusive and mysterious, if not downright bizarre. The more we have learned, the less we seem to understand.

The two theories are also fundamentally incompatible. In the classical mechanics of Isaac Newton, objects exist and things happen within a 'container' of absolute space and time which somehow sits in the background. If we could take everything out of Newton's universe we must suppose that the empty container would remain. General relativity gets rid of this container. In Einstein's universe space and time become relative, not absolute, and the theory is said to be 'background independent'. Spacetime is dynamic; it *emerges* as a result of physical interactions involving matter and energy.

Quantum mechanics, though exasperatingly bizarre yet unfailingly accurate in its predictions, is formulated in a different way. Interactions involving the elementary particles of matter and radiation are assumed to take place in precisely the kind of absolute spacetime container that general relativity eliminates. Quantum mechanics is background-dependent.

And there you have it. We have a classical (non-quantum) theory of spacetime which is background-independent. And we have a quantum theory of matter and radiation which is background-dependent. Our two most successful theories of physics are built on incompatible interpretations of space and time. They are woven on different kinds of fabric, one co-generated by the physics and the other pre-supposed and absolute.

We have two incompatible descriptions but, as far as we know (and certainly as far as we can prove), we've only ever had one universe. This is a problem because we also know that in the first few moments following its birth in the Big Bang, the universe would have existed at the quantum scale, at the mercy of a quantum mechanics. Now, the fact that we can't explain the origin and earliest moments of the universe might not trouble you overmuch, but the track-record of physics in the past hundred years or so has encouraged us to have greater expectations. What we *need* is a quantum theory of gravity.

So, do I have your attention yet?

The Chinese philosopher Laozi once said that a journey of a thousand miles begins with a single step. The first thing we can do is recognize that the only way to bring together quantum mechanics and general relativity is to find a new fabric, a new way of conceiving of space and time, one that is compatible with physics on any scale.

Charged with a newfound sense of purpose, we must now choose which road to take. Do we start with the pre-supposed, absolute spacetime fabric of quantum mechanics? Or do we start with the co-generated fabric of general relativity?

In the past forty years or so, judgments concerning the ease of passage along these two roads have split the theoretical physics community along essentially tribal lines. This split is very visible in a recent attempt to map the relationships between all the different ways of developing a quantum theory of gravity, which identified two distinct 'fundamental' branches: string theory and loop quantum gravity.[3] This divide isn't simply the result of differences of opinion between general relativists and particle theorists, as theorists on either side frequently borrow ideas and techniques from both general relativity and quantum field theory.

It is, however, true to say that the theoretical physics community is dominated by particle theorists, and particle theorists tend to favour the string theory approach. In the past twenty years or so, their highly successful PR has spilled into the popular science literature, with the result that few readers are even aware that there's more than one game in town, or more than one road that can be taken. For example, in one recent popular book about gravity, loop quantum gravity is mentioned only in passing, relegated to a footnote.[4] There are all sorts of reasons for this, and I will discuss some of these in what follows.

This book is about the road less travelled. It starts from general relativity, borrows ideas from quantum chromodynamics, and involves finding a way to turn the result into a quantum field theory of gravity. At the destination we find a fabric in which space is not continuous, but quantized. It comes in 'lumps' just like matter and radiation. The fabric is a system of interlinking 'loops' of gravitational force which form a 'spin network'. There are fundamental limits on the geometries of these loops, which define quanta of the area and volume of space in terms of something called the Planck length, which is about 1.6×10^{-35} metres, or about a hundredth of a billionth of a billionth of the diameter of a proton.

Different spin networks—different ways of interlinking the loops—define different quantum states of the geometry of space. The evolution of spin networks (the changing connections between one geometry and the next) then gives rise to a *spinfoam*. Adding spinfoams in something called a superposition describes an emergent spacetime, a fabric co-generated by the quantum physics.

This is loop quantum gravity, or LQG for short. It is now thirty years old and currently occupies the attentions of about thirty research groups around the world. The road from relativity has been difficult, with many highs and lows. There remain many challenges yet to be overcome, not least that of finding a way to torture the theory into providing one or more definitive empirical tests. But as Carlo Rovelli, one of the principal architects of LQG, explained a little while ago, 'the situation in quantum gravity is in my opinion . . . far better than twenty-five years ago, and, one day out of two, I am optimistic.'[5]

Readers of popular science may have heard about LQG from Lee Smolin, another of its principal architects, whose *Three Roads to Quantum Gravity* was published in 2000. Smolin briefly touched on LQG again in *The Trouble with Physics*, published ten years ago, and most recently in *Time Reborn*. Rovelli mentions LQG in his best-selling *Seven Brief Lessons on Physics*, and in his most recent book *Reality is Not What It Seems*.

My mission in *Quantum Space* is to correct an imbalance in public perception. I want to persuade you that LQG is not only a good game, it offers a genuine, credible alternative to the string theory approach. To do this I will share with you a little more detail about the theory than Smolin and Rovelli have so far shared in their own popular books. I not only want to give you some sense for what LQG tells us about space, time, and the universe, but also *how* and *why* it tells us these things.

In researching and writing this book I've been very fortunate to receive considerable encouragement, support, and insight from both Smolin and Rovelli. *This book is their story*, but we also need to get a couple of other things straight. LQG is the result of a collaboration involving many theorists over many years of effort. I've tried as far as possible to acknowledge as much of this effort as is feasible in a popular presentation, and can only offer my sincere apologies in advance to any member of the community reading this who feels that their efforts are under-represented or, even worse, overlooked. By the same token, as this book focuses principally on the efforts of two prominent contributors, it is not intended to provide a comprehensive summary of everything that's been done in the name of LQG.[6]

The book is structured in three parts. Part I sets the scene. It tells us about the things that Smolin and Rovelli learned about relativity, quantum mechanics, and Big Bang cosmology as young students and then as mature theorists. Readers already familiar with this background can safely skip it (but I hope they won't). Part II tells the story of the birth and evolution of LQG, starting with efforts to bring relativity and quantum mechanics together in the late 1950s, through Abhay Ashtekar's discovery of the 'new variables' that would make this possible, to the collaboration among Ashtekar, Smolin, and Rovelli (and many others) which yielded quanta of area and volume and the spinfoam formalism towards the turn of the previous century. Part III brings us reasonably up to date. It summarizes efforts to perform calculations of familiar physical quantities using LQG and the implications of the theory for quantum cosmology and the physics of black holes. On this part of the journey we will also explore the interpretation of quantum mechanics and the reality (or otherwise) of time.

I want to be straight with you about one final thing. Like the string or M-theory framework, LQG is still a work in progress. It is not finished and we don't yet have all the answers. Smolin and Rovelli are, of course, enthusiasts, and although I've tried to take a balanced view, a lot of their enthusiasm is inevitably reflected in my choice of words. But it is important not to get too carried away. Many other theorists who have been involved in various stages of the journey have since lost faith, the optimism of the late 1990s giving way to more sober (and sombre) assessments. Some have chosen to leave the field entirely and work on different problems. I hope that readers will at least get some sense of the scale of the challenge—chasing a theory of quantum gravity is most definitely *not* for the faint of heart. The book closes with a three-way exchange among Smolin, Rovelli, and myself which looks back at recent history, and forward to the future.

There's a lot at stake. The great revolutions in science that have shaped the way we seek to comprehend reality have profoundly changed the way we think about space, time, and the universe. Could another revolution be close at hand?

This book would not have been possible had Lee and Carlo not entrusted me with their stories. It's therefore a real pleasure to acknowledge their commitment to this project, reading over my shoulder as I worked on the manuscript, nudging me in the right direction and putting me right when I got it wrong. Having said that, it's important for you to know that the views expressed in this book are entirely my own, and whilst Lee and Carlo agree with much of what I've written, you shouldn't assume they agree with everything.

In addition to thanking Lee and Carlo, I also need to acknowledge the efforts of many other busy scientists who gave up their valuable time to read through my draft manuscript, correct many of my misinterpretations and mistakes, and add insights of their own. These include Abhay Ashtekar at Pennsylvania State University, John Baez at the University of California, Riverside, Martin Bojowald at Pennsylvania State University, Alejandro Corichi at the National Autonomous University of Mexico, George Ellis at the University of Cape Town, Ted Jacobson at the University of Maryland, Kirill Krasnov at the University of Nottingham, Jorge Pullin at Louisiana State University, and Peter Woit at Columbia University.

Now, LQG is a theory that is far from complete. This means that even those who have been involved most closely in its development don't all agree on the answers to the theory's many open questions. In order to produce a hopefully coherent, readable narrative about a subject in which virtually everything can be challenged, I've had to be somewhat selective in what to present. I'm pretty sure I haven't got this right all the time, and it goes without saying that I'm happy to take the credit for all those errors that remain.

I must also once more acknowledge my debts to Latha Menon, my editor at Oxford University Press, and to Jenny Nugee, who have again worked industriously behind the scenes to produce the book you now hold in your hands. Without their efforts, the book would certainly have been poorer.

Shall we begin?

Jim Baggott
July 2018

LIST OF ABBREVIATIONS

ADM	Arnowitt, Deser, Misner
ATLAS	A Toroidal LHC Apparatus (detector)
CDM	cold dark matter
CERN	Conseil Européen pour la Recherche Nucléaire
CMS	Compact Muon Solenoid (detector)
COBE	Cosmic Background Explorer
CODATA	International Council for Science Committee on Data for Science and Technology
GeV	giga electron volt
GUT	grand unified theory
Λ-CDM	lambda-cold dark matter
LHC	large hadron collider
LQC	loop quantum cosmology
LQG	loop quantum gravity
MeV	mega electron volt
MSSM	minimum supersymmetric standard model
NSF	National Science Foundation
QCD	quantum chromodynamics
QED	quantum electrodynamics
SLAC	Stanford Linear Accelerator Center
SUSY	supersymmetry
TeV	tera electron volt
WMAP	Wilkinson Microwave Anisotropy Probe

ABOUT THE AUTHOR

Jim Baggott is an award-winning science writer. A former academic scientist, he now works as an independent business consultant but maintains a broad interest in science, philosophy, and history and continues to write on these subjects in his spare time. His previous books have been widely acclaimed and include the following:

Mass: The Quest to Understand Matter from Greek Atoms to Quantum Fields, Oxford University Press, 2017
Origins: The Scientific Story of Creation, Oxford University Press, 2015
Farewell to Reality: How Fairy-tale Physics Betrays the Search for Scientific Truth, Constable, London, 2013
Higgs: The Invention and Discovery of the 'God Particle', Oxford University Press, 2012
The Quantum Story: A History in 40 Moments, Oxford University Press, 2011, re-issued 2015
Atomic: The First War of Physics and the Secret History of the Atom Bomb 1939–49, Icon Books, London, 2009, re-issued 2015 (shortlisted for the Duke of Westminster Medal for Military Literature, 2010)
A Beginner's Guide to Reality, Penguin, London, 2005
Beyond Measure: Modern Physics, Philosophy and the Meaning of Quantum Theory, Oxford University Press, 2004
Perfect Symmetry: The Accidental Discovery of Buckminsterfullerene, Oxford University Press, 1994
The Meaning of Quantum Theory: A Guide for Students of Chemistry and Physics, Oxford University Press, 1992

PROLOGUE

An Irresistible Longing to Understand the Secrets of Nature

It's probably not unreasonable to say that theoretical physics attracts particular kinds of people to work on it. This is a discipline that demands an agile, creative mind and a certain facility with abstruse concepts and dense, complex mathematics, so a degree of self-selection can be expected. A general lack of desire for material wealth is also useful. But if we're dealing with a physics perched right on the edge of our understanding of the nature of reality and physical existence, then we must admit that there's a further characteristically human trait that can often be helpful.

Theoretical physics *loves* a rebel.

Put it this way. You don't get the opportunity to transform our understanding of the very fabric of space and time; you don't get to turn the world upside-down and subvert our cosy notions of the larger universe if you're inclined to worry about what other people will think.

Many rebels come to theoretical physics seeking a refuge, a safe haven from the perceived injustices and unpredictability of human affairs and the social disappointments of youth. They come seeking a place where their instincts are more likely to be appreciated as, unlike many other walks of life, rebellion in science is not only encouraged, it is *necessary*.

At Walnut Hills High School in Cincinnati, Ohio, the sixteen-year-old Lee Smolin was principally interested in revolutionary politics, rock stardom, mathematics, architecture, and his girlfriend, not necessarily in this order or with this priority. His teachers had advised him that he wasn't smart enough to take the advanced track in mathematics and, to prove them wrong, in a singular act of rebellion he completed the three-year advanced course in just a year. Not everyone's idea of radicalism in action, perhaps, and not as subversive as rock music or publishing an underground newspaper, but Smolin discovered that 'it was almost as much fun'.[1]

His interest in architecture was kindled when, in the eleventh grade, he invited the eccentric architect and system theorist Richard Buckminster Fuller to speak at the school. A fascination with Fuller's geodesic domes led him to a branch of mathematics called tensor calculus. Books on tensor calculus led him to Einstein's theories of relativity, and to Einstein himself.

Smolin's world crumbled at the beginning of his senior year. His rock band had split, his girlfriend had left him, and his political revolution had failed to come to pass. He had flunked chemistry, and a perceived lack of aptitude meant that he had been refused admission to the physics class. He decided to drop out of high school altogether.

It was therefore in the public library that he would find the book that would change his life. It was called *Albert Einstein: Philosopher-Scientist,* edited by Northwestern University philosopher Paul Arthur Schilpp, and first published in 1949. The book opens with a chapter of 'Autobiographical Notes', written by the 67-year-old Einstein as 'something like my own obituary'.[2] His words spoke directly to the disillusioned Smolin.

Einstein wrote of the 'nothingness of the hopes and strivings which chases most men restlessly through life'. As a young man he had himself 'soon discovered the cruelty of that chase, which in those years was much more carefully covered up by hypocrisy and glittering words than is the case today'. Rejecting any solace that might be found in organized religion, Einstein had instead found comfort in physics:[3]

> Out yonder there was this huge world, which exists independently of us human beings and which stands before us like a great, eternal riddle, at least partially accessible to our inspection and thinking. The contemplation of this world beckoned like a liberation, and I soon noticed that many a man whom I had learned to esteem and admire had found inner freedom and security in devoted occupation with it.

Smolin decided to become a theoretical physicist later that evening. Like Einstein, he was 'motivated by an irresistible longing to understand the secrets of nature'.[4] '[I]t occurred to me then and there that if I could do nothing else with my life, perhaps I could do that.'[5]

It was not an entirely auspicious decision. He had already been accepted to study architecture at Hampshire College, a radical liberal arts college in Amherst, Massachusetts, and he now scrambled to switch subjects. But he was not totally unprepared. His mother, a Professor of English at the University of Cincinnati, helped enroll him on a graduate course on general relativity, taught at the university by Paul Esposito. This was his first physics course.

He also spent the hot summer months between school and college in Los Angeles working as a sheet metal apprentice at Van Nuys Heating and Air Conditioning, reading about basic physics, relativity, and quantum mechanics in his spare time.

Carlo Rovelli's journey to theoretical physics took place on a different continent, in a different language, and differs in its details. Yet it shares some remarkable similarities.

He, too, had come to have little faith in a world organized by adults in ways that seemed far from just and right. As he grew up in Verona, in northern Italy not far from Venice, he railed against the creeping nostalgia for fascism that had leached into all parts of provincial society. He clashed frequently with his teachers and rebelled against the authority of the classical lyceum, his upper secondary school, teaching basic subjects in preparation for university. He also needed to escape from his own family. A mother's love for her only child is comforting, but it can also be stifling.[6] Rovelli needed to breathe.

He read voraciously on politics, sociology, and science, and devoured novels and poetry. At the age of twenty he set off on a nomadic quest around the world in search of truth. On his travels he acquired a strong sense of liberty; he learned how to take his life in his own hands and follow his dreams. But by putting some distance between himself and the place that represented everything he had come to resent, he began to see things a little differently. There was still plenty to be angry about, but he began to realize that there were also rich possibilities for learning back in Italy. And he was also missing his Italian girlfriend.

On his return he enrolled to study for a degree in physics at the University of Bologna, the world's oldest, founded in 1088. This was more accident than design. At school he had demonstrated some capability in physics and mathematics but his first love was philosophy. He had chosen not to enroll for a philosophy degree because he simply didn't trust established educational institutions to treat philosophical problems with the importance and seriousness the young idealist demanded.

Bologna is a city famed for its art, culture, and historic architecture—notably its red-tiled roofscape, reflecting the colour of its communist politics. It suited him well. During his time as a student he made common cause with a like-minded community, one which embraced a post-hippy counterculture. The group experimented with mind-altering drugs, and different ways of living, and loving, as they tended their goat, Lucrezia. They dreamt of a peaceful, cultural revolution that would make the world a better place.

Despite the distractions of commune-style living, Rovelli had no problem maintaining his focus on physics. He would become so absorbed in study that he would remain blissfully unaware of everything else going on around him. One day, a builder arrived to demolish an interior wall in the dilapidated house in which they were living. This took several hours of noisy effort. Rovelli was working in the room, sitting just a few metres from the wall in question. When asked if the builder had disturbed him, he looked up from his books and asked: 'What builder?'[7]

In February 1976 he joined the group that established Radio Alice, a free radio station which provided: an 'open microphone for everybody, where experiences and dreams were exchanged'.[8] Topics included labour protests and political analysis, poetry, yoga, cooking, declarations of love, and music by Beethoven and Jefferson Airplane.

This was one of the defining periods of Rovelli's life, but as the dream faded he learned that 'one does not change the world so easily'.

Confused and greatly disillusioned, Rovelli now had to come to terms with the challenge of deciding what to do with the rest of his life. The timing was perhaps fortuitous. He had chosen to learn physics because he had to study something (other than philosophy), and he preferred to postpone the call to obligatory military service. But in the third year of his degree, he was at last exposed to the conceptual revolutions that had shaken physics earlier in the twentieth century. In quantum mechanics and in Einstein's relativity he would find the places where physics and philosophy not only collide, they become barely distinguishable.

Once again, Einstein provided inspiration. Shortly after completing work on relativity, Einstein wrote a popular account of his theories. He called it a 'booklet'. It was first published in German in the spring of 1917, entitled *Relativity: The Special and the General Theory (A Popular Exposition)*. He wasn't entirely satisfied with the result, and later joked that although the cover described the book as 'generally understandable', it was in fact '*gemeinunverständlich*' (generally not understandable).

The book was nevertheless enormously successful, and went through many editions, translations, and reprintings. Along the way it picked up a series of appendices as readers (and publishers) demanded a little more clarity of explanation of the mathematics, and as the observational and experimental evidence in support of relativity accumulated.

In 1953 (when Einstein was 74) he penned a fifth appendix entitled 'Relativity and the Problem of Space'. This is quite different in style from the others and contains some deep philosophical observations on the nature of space and time. It represents the result of almost fifty years of further reflection made towards the end of his life. Einstein died two years later.

In this appendix Einstein addressed questions that had teased the intellects of philosophers for centuries. 'It is indeed an exacting requirement', he wrote, 'to have to ascribe physical reality to space in general, and especially to empty space. Time and again since remotest times philosophers have resisted such a presumption.'[9]

That was it. Rovelli was captivated. This kind of physics spoke to him of 'the possibility of not giving up the desire for change and adventure, to maintain my freedom of thinking and to be what I am'.[10]

Neither of them knew it yet, but their passion for adventure in the search for the secrets of nature would eventually bring Smolin and Rovelli together, in one of the most productive and pleasurable of modern-day scientific collaborations.

To appreciate what these theorists have achieved in a collaboration spanning thirty years, we must first understand what they learned as students about two of the greatest theories of physics ever devised—relativity and quantum mechanics—and the dark secret that has kept these theories apart.

PART I

FOUNDATIONS

1

THE LAWS OF PHYSICS ARE THE SAME FOR EVERYONE

It's not hard to understand why Smolin and Rovelli would be drawn to the revolutions in scientific thinking inspired by Einstein. As they listened to their teachers in class, read diligently, and worked their way through the classic textbook problems, their minds were opened upon a landscape of extraordinary possibility.

They found themselves asking fundamental questions about the nature of the seemingly obvious—space and time—the very fabric of our physical reality. Despite familiar appearance, Einstein had shown that the answers to these questions are *not* obvious. He had shown that it is possible to subvert authority and overcome prejudice in pursuit of a deeper and more profound truth. He had set out on his path to revolution at the age of just 26 and, although his legacy is virtually without parallel in the history of science, it was clear to the young students that his work was unfinished. There was one final step that had yet to be taken.

Einstein opens Appendix 5 of *Relativity* with the following observation: 'It is a characteristic of Newtonian physics that it has to ascribe independent and real existence to space and time as well as to matter'.[1] The so-called 'classical' system of physics that the English mechanical philosopher Isaac Newton had helped to construct in the seventeenth century, some two hundred years before Einstein, demands a fabric of *absolute* space and time. This notion appears so consistent with ordinary experience that anyone unfamiliar with relativity will likely never give it a second thought.

But there are real philosophical (and, as it turns out, very practical) reasons why we should reject this notion completely.

An absolute space forms a kind of 'container' within which some sort of mysterious cosmic metronome marks absolute time. This is a container within which actions impress forces on matter and things happen. But if we were somehow able to take all the matter out of the universe, we are obliged to presume that the empty container would remain, and the metronome would continue to lay down its cosmic click-track. There would still be 'something'.

But what, exactly? There's a logic that suggests that everything there is really ought to exist *within* the universe, kind of by definition. But the notions of absolute space and time imply the opposite—that the universe instead exists within the container. If we push this logic a little further, we can imagine a vantage point from which we could look down on the entire universe: a 'God's-eye view' of all creation.

We could just shrug our shoulders at this point and argue that, grand philosophical (and theological) implications aside, absolute space and time at least appear to be consistent with our everyday experience. We're generally able to find things in the places we left them. We always follow the same route to and from work. Our days always start in the mornings. Surely, these are unassailable absolutes of our physical reality?

But even this isn't true. A moment's reflection will tell us that, despite superficial appearances, we only ever see objects moving towards or away from each other, changing their relative positions. This is *relative* motion, occurring in a space and time that are in principle defined only by the relationships between the objects themselves. Newton was obliged to acknowledge this in what he called our 'vulgar' experience.

So, we might think to reduce our vulgarity and impose some order by using a coordinate system (based, for example, on three spatial dimensions, which we define with the aid of coordinate axes, labelled *x*, *y*, and *z*) and by noting that an object in this place at this time moves to this other place a short time later. That's better. Or, at least, this is starting to sound a little more scientific.

But don't get too comfortable. Because we now must admit that any such coordinate system is entirely arbitrary.

We measure places on Earth relative to a different kind of coordinate system, of latitude and longitude, defined by the shape and size of our planet. We measure time relative to a system based on the orbital motion of the Earth around the Sun and the spin motion of the Earth as it turns on its axis. These systems might seem to be perfectly 'natural' choices, but they are natural only for us Earth-bound human beings and we cannot escape the simple truth that they are also quite arbitrary. Systems of coordinates like *x*, *y*, and *z*, latitude and longitude, and so on define so-called *frames of reference* within which we can locate objects and see things happening.

We can go further. An object in uniform motion in a straight line appears to move from here to there. But what, exactly, is moving? Is it the object, travelling from here to there at a certain speed? Or is the object actually stationary, and 'there' is moving 'here' at this same speed?

Fans of J. R. R. Tolkein's *The Lord of the Rings* may remember Pippin's experiences, sat before Gandalf on the back of Shadowfax, riding in haste to Minas Tirith: 'As he fell slowly into sleep, Pippin had a strange feeling: he and Gandalf were still as stone, seated upon the statue of a running horse, while the world rolled away beneath his feet with a great noise of wind'.[2]

In such examples of uniform motion, there is in principle no observation or measurement we can make that will tell us who or what is moving. Of course, simple logic dictates that it is Shadowfax that is galloping on a stationary Middle-earth, but there's no escaping the rather stubborn fact that we can't actually *prove* this.

Such uniform motion is entirely relative, and physicists define it in the context of so-called *inertial* frames of reference. We conclude from all this that there can be no absolute coordinate system of the universe, no absolute or ultimate inertial frame of reference, and therefore no absolute motion. There is no 'God's-eye view'.

Any concept that is not accessible to observation or experiment in principle, a concept for which we can gather no empirical evidence, is typically regarded to be *metaphysical* (meaning literally 'beyond physics'). Why, then, did Newton insist on a system of absolute space and time, a metaphysical system we can never directly experience? Because by making this assumption he found that he could formulate some relatively simple—and very highly successful—*laws of motion*.

Success breeds a certain degree of comfort, and a willingness to overlook the sometimes grand assumptions or pre-commitments on which theoretical descriptions are based. Nevertheless, towards the end of the nineteenth century a growing and vociferous empiricist philosophy—one which rejected completely all metaphysical constructions and sought to exclude them from science—was shifting the weight of scientific opinion.

Momentum was building, but then Scottish physicist James Clerk Maxwell threw a hefty spanner in the works.

Confronted by compelling experimental evidence for deep connections between the phenomena of electricity and magnetism, over a ten-year period from 1855 Maxwell published a series of papers which describes these in terms of two distinct, but intimately linked, electric and magnetic *fields*. We denote such fields by drawing 'lines of force' stretching (by convention) from positive to negative, or from north pole to south pole (see Figure 1). Such fields are not creatures of a fertile imagination: we can *feel* the magnetic field when we try to push the north poles of two bar magnets together.

But this is now no longer all about material objects moving about in a three-dimensional space in a one-dimensional time. Maxwell's electromagnetic field equations tell of a very different kind of physics. A magnetic field is felt in the 'empty' space around the magnet (we can quickly verify that the field persists in a vacuum—unlike sound, it doesn't require air to 'carry' it). In fact, Maxwell's equations can be manipulated in such a way that they quite clearly describe the motions of *waves*.

This gelled quite nicely with a growing body of experimental evidence in support of a wave theory of light, and light is just one form of electromagnetic radiation. Maxwell's equations can be further manipulated to calculate the speed of electromagnetic waves travelling in a vacuum. It turns out that the result is precisely the speed of light, to which we give the special symbol *c*.

But it's rare in science (as indeed it is in life) that such a moment of clarity doesn't have to be paid for with confusion elsewhere. The wave nature of electromagnetic radiation now seemed to be clear and unarguable. But then physicists had to admit that these must be waves *in* something.

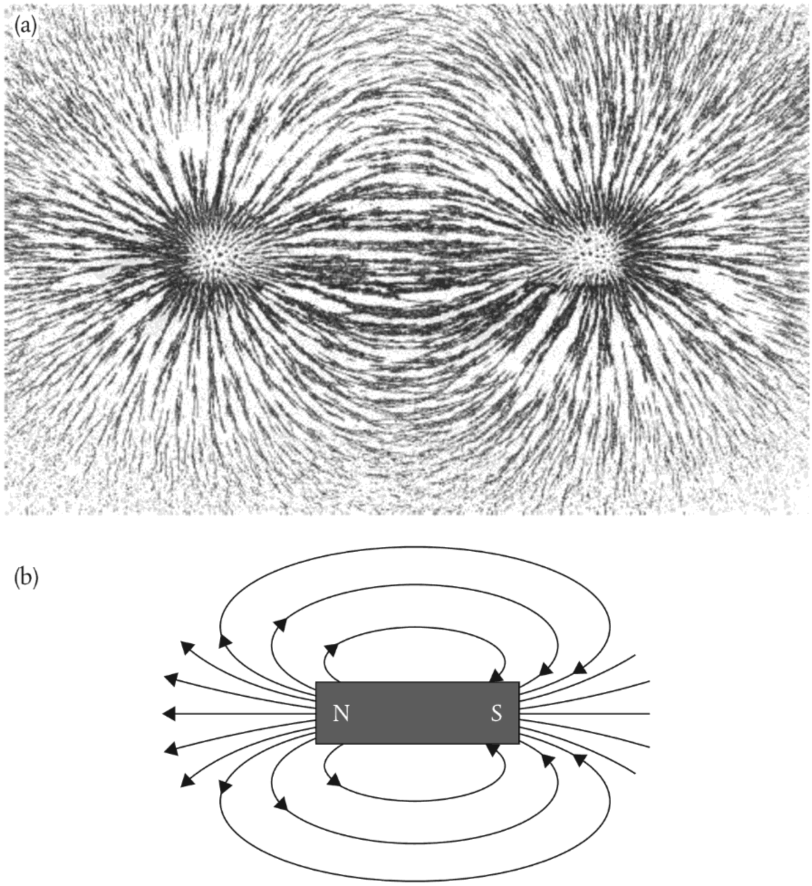

Figure 1. (a) Iron filings sprinkled on a sheet of paper held above a bar magnet reveal the 'lines of force' of the magnetic field stretching between the north and south poles. This pattern is shown schematically in (b). By convention the lines of force 'flow' from north to south.

We throw a stone into a lake and watch as the disturbance ripples across the surface of the water. The waves caused by this action are clearly waves in a 'medium'—the water in this case. There could be no escaping the conclusion. Electromagnetic waves had to be waves in some kind of medium. Maxwell himself didn't doubt that electromagnetic waves must move through the *ether,* a purely hypothetical, tenuous form of matter thought to fill all of space.

And here's the confusion, the price to be paid. All the evidence from experimental and observational physics suggested that if the ether really exists, then it couldn't be participating in the motions of observable objects. The ether *must* be stationary. If the ether is stationary, then it is also by definition absolute: it fills precisely the kind of container demanded by an absolute space. A stationary ether would define the ultimate inertial frame of reference.

Hmm.

But the problem is now subtly different. Newton required an absolute space that sits passively in the background and which, by definition, we can never experience. Now we have an absolute space that is supposed to be *filled with ether*. That's a very different prospect.

So here's a thought. If the Earth spins on its axis in a stationary ether, then we might expect there to be an *ether wind* at the surface (actually, an ether drag, but the consequences are the same). The ether is supposed to be very tenuous, so we wouldn't expect to feel this wind like we feel the wind in the air. But, just as a sound wave carried in a high wind reaches us faster than a sound wave travelling in still air, we might expect that light travelling in the direction of the ether wind should reach us faster than light travelling against this direction. A stationary ether suggests that the speed of light should be different when we look in different directions.

Any differences were expected to be very small, but nevertheless still measurable with late-nineteenth-century optical technology. But in 1887 American physicists Albert Michelson and Edward Morley could find no differences. Within the accuracy of their measurements, the speed of light was found to be constant, independent of direction. Their result suggests that there is actually no such thing as a stationary ether.

It's just this kind of conundrum that brings science to life. Newton's laws of motion demand an absolute space and time that we can't experience or gain any empirical evidence for. Maxwell's electromagnetic waves demand a stationary ether to move in, but experiment tells us that there can be no such thing. What to do?

At this point in stepped a young 'technical expert, third class' working at the Swiss Patent Office in Bern. Fed on a diet of physics and empiricist philosophy, in 1905 Einstein judged that the solution required a firmly practical and pragmatic approach in which the 'observer' takes centre stage. Here 'observer' doesn't necessarily mean a human observer. It means that, to understand the physics correctly, we must accept that this is physics as seen from the perspective of someone or something that is observing or making measurements, with a ruler and a clock.

Of course, such an observer is implicit in the physics of Newton. But Newton's laws are formulated as though the observer is somehow 'outside' of the reality in which all the action is taking place (hence, 'God's-eye view'). Einstein put the observer back into the thick of it, *inside* the reality that is being observed.

Einstein began by stating two basic principles. The first, which he called the *principle of relativity*, says that observers who find themselves in relative motion at different (but constant) speeds *must* make measurements that conform to the laws of physics. Put another way, the laws of physics must be the same for everyone, irrespective of how fast they're moving relative to what they're observing (or the other way around). This is, surely, what it means for a relationship between physical properties to be a 'law'.

Smolin and Rovelli, whose aspirations for political revolution had broken so disappointingly on the rocks of human intransigence, would have appreciated this statement when they encountered it for the first time. At least in the world of physics, true democracy reigns.

The second principle relates to the speed of light. In Newton's mechanics, speeds are simply additive. An object rolling along the deck of a ship as the ship ploughs across the Atlantic Ocean is moving with a total speed given by the speed of the roll along the deck plus the speed of the ship. But light doesn't obey this rule. The conclusion drawn from the Michelson–Morley experiment is that light always travels at the same speed. The light emitted from a flashlight moves away at the speed of light, *c*. Light from the same flashlight lying on the deck of the ship still moves at the speed of light, not *c* plus the speed of the ship.

Instead of trying to figure out *why* the speed of light is constant, Einstein simply accepted this as an established fact and proceeded to work out the consequences.

The speed of light is so incredibly fast compared with the 'everyday' speeds of objects with which we're more familiar. Normally, this means that what we see appears simultaneously with what happens. This happens over here, and we see this 'instantaneously'. That happens over there shortly afterwards, and we have no difficulty in being able to order these events in time: this first, then that. Einstein was asking a very simple and straightforward question. However it might appear to us, the speed of light is *not* infinite. If it actually takes some time for light to reach us from over here and over there, how does this affect our observations of things happening in space and in time?

Einstein discovered that one immediate consequence of a fixed speed of light is that there can be no such thing as absolute time.

Suppose you observe a remarkable occurrence. During a heavy thunderstorm you see two bolts of lightning strike the ground simultaneously, one to your left and one to your right (see Figure 2). You're standing perfectly still, so the fact that it takes a small amount of time for the light to reach you is of no

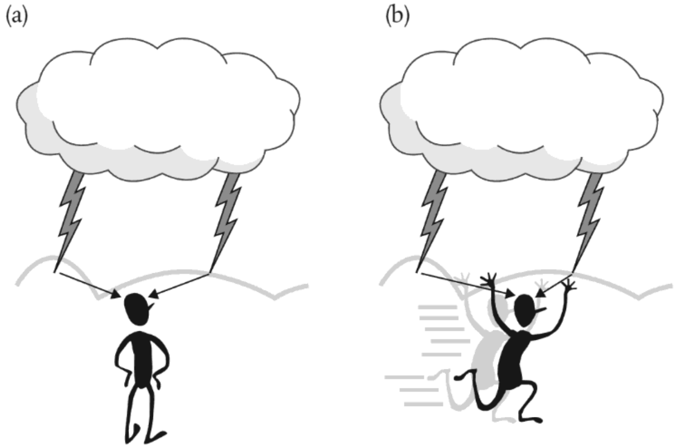

Figure 2. The stationary observer in (a) sees the lightning bolts strike simultaneously, but the observer in (b), who is moving at a considerable fraction of the speed of light, sees the right-hand bolt strike first.

real consequence. Light travels very fast so, as far as you're concerned, you see both bolts at the instant they strike.

However, I see something rather different. I'm moving at very high speed—half the speed of light, in fact—from left to right. I pass you just as you're making your observations. Because I'm moving so fast, by the time the light from the left-hand bolt has caught up with me I've actually moved quite a bit further to the right, and so the light has a little further to travel. But the light from the right-hand bolt has less ground to cover because I've now moved closer to it. The upshot is that the light from the right-hand bolt reaches me first.

You see the lightning bolts strike simultaneously. I don't. Who is right?

We're both right. The principle of relativity demands that the laws of physics must be the same for everyone, irrespective of the relative motion of the observer and, like Pippin riding on Shadowfax, we can't use physical measurements to tell whether it is you or me who is in motion.

We have no choice but to conclude that there is no such thing as absolute simultaneity. There is no definitive or privileged inertial frame of reference in which we can declare that these things happened at precisely the same time. They may happen simultaneously in this frame or they may happen at different times in a different frame, and all such frames are equally valid. Consequently, there can be no 'real' or absolute time. We perceive events differently because time is relative.

You may already be familiar with the consequences of this relativity, which later became known as 'special' relativity because it doesn't deal with objects that are accelerating.* An observer moving relative to a series of events will measure these to unfold in a time that is longer (time is dilated) when compared with the measurements of a stationary observer. The length of an object moving relative to a stationary observer will appear to contract compared with the measurements of an observer riding on the object.

The extent of time dilation and distance contraction depend on the ratio of the relative speed of the observer and the speed of light. These only become noticeable when the relative speed is close to that of light. A stationary observer won't notice the length of your car contracting, no matter how fast you drive past.

This is all a bit disconcerting, and it's tempting to slip back into older, more comfortable ways of thinking. If this is all about observation and measurement at speeds close to that of light, then surely this is just a matter of perspective and perception? From the perspective of this inertial frame of reference, time *appears* to slow down and distances *appear* to contract. Surely, time doesn't really slow down and distances don't really contract?

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* But stay tuned.

Ah, but they do. Space and time are relative, not absolute, and there is therefore no unique or 'correct' perspective which will give us absolute measures of distance and time. The consequences are very practical. To be fair, it's hard to gather experimental evidence for the effects of distance contraction, but the effects of time dilation can certainly be measured.* If we put an atomic clock on a plane and fly it from London to Washington, DC and back, we find that the clock loses 16 billionths of a second compared with a stationary clock left behind at the UK's National Physical Laboratory. This is due to the fact that time slows down aboard the plane as it crosses and re-crosses the Atlantic.[3]

This is a lot to take in, and the consequences are pretty mind-blowing. The young Rovelli realized that special relativity does not sit well with the notion of a single 'present', defined everywhere. In many ways the present is an illusion, just as the flat Earth is an illusion wrought from our inability to perceive the curvature of the Earth from our vantage point on its surface. If we were somehow able to perceive time in billionths of a second, we might realize that 'saying "here and now" makes sense, but that saying "now" to designate events "happening now" throughout the universe makes no sense.'[4] Trying to establish an absolute basis for time-ordering events unfolding in the universe is as futile as trying to discover what lies north of the North Pole.

Einstein thought long and hard about these consequences, and later in 1905 published a short addendum to his paper on relativity. He applied this same logic to an object emitting two bursts of light of equal energy in opposite directions, such that the object is not diverted from its straight-line path. He deduced that the

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* Simply because distance contraction happens on scales at which we must consider that other great theory of the twentieth-century—quantum mechanics—and this confuses things quite a bit.

total energy carried away by the light bursts is measured to be *larger* when observed from an inertial frame of reference moving relative to the object, just as time is dilated.

But then there is a law of physics that says that energy *must* always be conserved. Energy cannot be created or destroyed. So, if the energy carried away is measured to be larger, where then does this extra energy come from? We might instinctively assume that the object must slow down, losing some of its energy of motion—called kinetic energy—which is somehow transferred to the bursts of light. But this is not what Einstein discovered. He found that the energy does indeed come from the object's kinetic energy, but the object doesn't slow down. The energy comes instead from the *mass* of the object, which falls by an amount given by $m = E/c^2$.

Einstein concluded:[5]

> If a body emits the energy [E] in the form of radiation, its mass decreases by [E/c^2]. Here it is obviously inessential that the energy taken from the body turns into radiant energy, so we are led to a more general conclusion: The mass of a body is a measure of its energy content.

Today we would probably rush to re-arrange this expression to give the iconic formula $E = mc^2$.

At the time of its publication in 1905 the special theory of relativity was breathtaking in its simplicity—the mathematics in it isn't all that complicated—yet it is profound in its implications. As young students Smolin and Rovelli marvelled at the logic and were fascinated by the conclusions.

But if Newton had been watching over Einstein's shoulder, he might still have indulged a little smile.

As I mentioned earlier, Einstein's theory is 'special' because it deals only with systems in uniform motion. It does not—it cannot—deal with systems undergoing acceleration. Although we might be prepared to admit the relativity of uniform motion in a straight line, anyone who has ever ridden a roller coaster will tell you that acceleration is something that we *feel*. Pippin had no sense of his own uniform motion riding on the back of Shadowfax, but when we're subject to a sudden *change* of speed or direction, or when we find ourselves spinning around in a circle, we *know* it.

But acceleration relative to what? Rotation relative to what? Despite the success of the special theory, Einstein hadn't yet completely closed the door on absolute space and time.

There's more. In addition to his laws of motion, Newton had also derived a law of universal gravitation. This states that objects experience a force of gravity that is proportional to their masses and inversely proportional to the square of the distance between them—we multiply the masses and divide by the distance-squared.

This was another great success, but it also came with another hefty price tag. Newton's force of gravity is distinctly different from the kinds of forces involved in his laws of motion. The latter forces are *impressed*; they are caused by actions involving physical contact between the object at rest or moving uniformly and whatever it is we are doing to change the object's motion.

Newton's gravity works differently. The force of gravity is presumed to pass instantaneously between the objects that exert it, through some kind of curious action-at-a-distance. It was not at all clear how this was supposed to work. Critics accused him of introducing 'occult forces' in his system of mechanics.

Newton had nothing to offer. In a general discussion (called a 'general scholium'), which he added to the 1713 second edition of his famous work *Mathematical Principles of Natural Philosophy*, he wrote: 'I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses.'[6]

Because Newton's force of universal gravitation is supposed to act *instantaneously* on objects no matter how far apart they might be, this classical conception of gravity is completely at odds with special relativity, which denies that the influence of any force can be transmitted faster than the speed of light.

Special relativity could not cope with acceleration and it could not accommodate Newton's force of gravity. Einstein still had plenty of work to do.

2

THERE'S NO SUCH THING AS THE FORCE OF GRAVITY

Newton was all too aware that he was vulnerable on the question of absolute space, but acceleration (and, particularly, rotation) was his secret weapon.* In an attempt to pre-empt his critics, he devised a thought experiment to show how the very possibility of rotational motion proves the existence of absolute space. This is Newton's famous 'bucket experiment'.

In his *Autobiographical Notes,* Einstein mentions this only in passing: 'First in line to be mentioned is Mach's argument, which, however, had already been clearly recognized by Newton (bucket experiment).'[1]

Einstein doesn't refer to Newton's bucket in Appendix 5 of *Relativity,* but he does credit Austrian Ernst Mach as the only

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* Acceleration is the rate of change of speed with time. We tend to think of this as involving a change in the magnitude of the speed (for example, when we accelerate in a car from 0 to 60 miles per hour). But speed is a *vector* quantity—it is described in terms of both magnitude *and* direction. If we keep the same speed but rapidly change direction, this is still acceleration. So rotation, in which the direction of motion is constantly changing, is a very particular kind of acceleration.

physicist 'who thought seriously of an elimination of the concept of space, in that he sought to replace it by the notion of the totality of the instantaneous distances between all material points. (He made this attempt in order to arrive at a satisfactory understanding of inertia.)'[2]

Newton's thought experiment runs something like this. We tie one end of a rope to the handle of a bucket and the other end around the branch of a tree, so that the bucket is suspended in mid-air. We fill the bucket three-quarters full with water. Now we turn the bucket so that the rope twists tighter and tighter. When the rope is twisted as tight as we can make it, we let go and watch what happens (Figure 3).

The bucket begins to spin around as the rope untwists. At first, we see that the water in the bucket remains still. Then, as the bucket picks up speed, the water itself starts to spin and its surface becomes concave—the rotational motion appears to exert a centrifugal force which pushes the water out towards the circumference and up the inside of the bucket. Eventually, the rate of spin of the water catches up with the rate of spin of the bucket, and both spin around together.

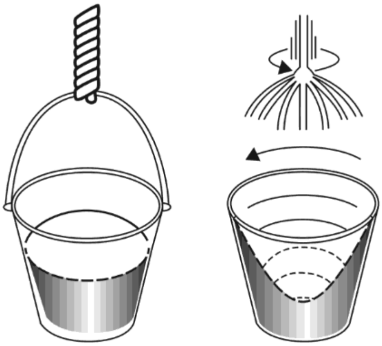

Figure 3. Newton's bucket. As the rope untwists, the bucket rotates and the water inside is driven up the inside, forming a concave shape.

In the *Mathematical Principles,* Newton wrote:[3]

> This ascent of the water [up the inside of the bucket] shows its endeavour to recede from the axis of its motion; and the true and absolute circular motion of the water, which is here directly contrary to the relative, discovers itself, and may be measured by this endeavour.

This is such an ordinary or everyday kind of observation that it would seem to prove nothing, let alone the existence of absolute space. But the logic is quite compelling. The water pushed up the inside of the bucket is obviously moving, and we accept that this motion must be *either* absolute *or* relative. The water continues to be pushed up the inside of the bucket as its rate of spin *relative to the bucket* changes, and it remains in this state when the water and the bucket are spinning around at the same speed. Newton argued that the origin of this behaviour cannot therefore be traced to the motion of the water relative to the bucket. If this motion isn't relative, then it must be absolute. And if absolute motion is possible, then absolute space must exist.

Einstein was aware of the flaw in Newton's logic, but the counter-argument takes some swallowing. Many years later it was argued that Newton had neglected to consider the bigger picture. Yes, the behaviour of the water in the bucket cannot be explained by considering only its motion relative to the bucket. But it can potentially be explained by considering its motion *relative to the rest of the universe.*

Remember, if all motion (including rotation) is relative, then there is in principle no observation or measurement we can make which tells us who or what is moving. This is what 'relative motion' means. Newton's argument fails if it turns out that we can't distinguish between the situation in which the bucket is spinning relative to the rest of the universe, and the situation in which the rest of the universe is spinning relative to the stationary bucket.

Of course, this leads us to the rather bizarre conclusion that spinning the entire universe around a stationary bucket would somehow exert a centrifugal force on the water inside it. We're left to ponder just how that might work.

As is evident from Einstein's comments, this counter-argument is most closely associated with the physicist (and arch-empiricist) Mach, and is sometimes referred to as *Mach's principle*.[4] To eliminate absolute space entirely, Einstein needed to find a situation in which an observer experiencing acceleration wouldn't be able to tell who or what was being accelerated.

Now, all our experience on Earth suggests that acceleration (or inertia—a measure of an object's *resistance* to a change in its state of motion) is something that we feel directly and is therefore undeniable. But what happens if we find ourselves falling freely in outer space?

We can't know what Einstein was thinking, but we do know that on an otherwise perfectly ordinary day at the Swiss Patent Office in November 1907, Einstein had what he later called his 'happiest thought'.[5] He had by this time received a promotion, to 'technical expert, second class'. As he later recounted: 'I was sitting in a chair in my patent office at Bern. Suddenly a thought struck me: If a man falls freely, he would not feel his weight. I was taken aback. This simple thought experiment made a deep impression on me.'[6]

In free fall we feel neither acceleration nor gravity. From this very simple intuition, Einstein realized that our experience of acceleration is precisely the same as our experience of gravity. They are one and the same thing. He called it the *equivalence principle*. This meant that solving the problem of acceleration in relativity might also solve the problem of Newton's gravity. Perhaps there were not two distinct problems to be solved, after all. Smolin recalls reading Einstein's 1907 paper on the equivalence principle whilst riding the New York City subway, and 'getting it'.[7]

Einstein had found the equivalence principle but he was unsure what to do with it. In any case his life changed quite dramatically towards the end of 1907, as his growing reputation allowed him to establish the beginnings of an academic career, at universities first in Zurich and then in Prague. He acquired many teaching and administrative responsibilities and was drawn to other problems in physics. It would take him another five years to figure out that the equivalence principle implies another extraordinary connection, between gravity and *geometry*.

But the geometry of what, exactly? The answer to this question was supplied in 1908 by Hermann Minkowski, Einstein's former mathematics teacher at the Zurich Polytechnic. In special relativity time dilates and distances contract, but Minkowski realized that it is possible to combine space and time together in such a way that these effects compensate. The result is a four-dimensional *spacetime*, sometimes called a *spacetime metric*.

Einstein later took pains to point out that this kind of 'four-dimensional' view of space and time was not particularly new. An event taking place in Newton's classical physics of everyday requires four numbers to describe it completely: three spatial coordinates x, y, and z and a time t. But in Newton's physics time is treated quite distinctly and independently of space. In Minkowski spacetime, time (t, in seconds) is multiplied by the speed of light (c, in metres per second) and so the product ct has the same units as a spatial dimension (metres), just like x, y, and z. In Minkowski spacetime, time is treated on an 'equal footing'.

If gravity is equivalent to acceleration, then Newton's (probably apocryphal) experience of the apple falling from the tree in the garden at Woolsthorpe Manor can be viewed in two distinctly different, but physically equivalent, ways. We can imagine that the force of gravity somehow reaches up and pulls the apple down to the ground. Alternatively, we can imagine that the ground accelerates upwards to meet the apple. Both are equivalent, but the latter perspective can only be applied if we regard the Earth to be flat. Of course, the Earth is curved, and we can't ignore the perfectly legitimate experiences of all the people on the other side of the world.

Einstein began to understand that the problem lay in the nature of spacetime itself. Minkowski spacetime is 'flat', or Euclidean, named for the famed Greek mathematician Euclid of Alexandria. In school we learn that the angles of a triangle add up to 180°. We learn that the circumference of a circle is 2π times its radius, and that parallel lines never meet. These are all characteristics of a flat space, and when we add a fourth dimension of time we get a flat spacetime.

As he had already done so often to great effect, Einstein once again turned the problem on its head. It is possible to demonstrate the equivalence of acceleration and gravity in a system in which a flat Earth moves through a flat spacetime. But we know that the surface of the Earth is curved. So, where does that leave spacetime?

In a flat spacetime the shortest distance between two points is obviously the straight line we can draw between them. But the shortest distance between London, England and Sydney, Australia—a distance of 10,553 miles—is not, in fact, a straight line. The shortest distance between two points on the surface of a sphere is a curved path called an *arc of a great circle* or a *geodesic*.

This was the solution that Einstein had sought. In a flat spacetime all lines are straight, so Newton's force of gravity is obliged to act instantaneously, and at a distance. But if spacetime is

Kip Thorne, and Rainer Weiss for their contributions to LIGO and the observation of gravitational waves.

The successful detection of gravitational waves is not only an extraordinary vindication of general relativity; it also opens a new window on events in distant parts of the universe, one that doesn't rely on light or other forms of electromagnetic radiation to tell us what's happening.

When Einstein delivered the last of his lectures on general relativity at the Prussian Academy of Sciences, he believed he had finally settled the matter of absolute space and time. He wrote that the theory's principle of general covariance: 'takes away from space and time the last remnant of physical objectivity'.[15] He thus declared the defeat of the absolute and the triumph of the relative.

But now we must return to Mach's principle. If Newton's bucket is stationary and the rest of the universe is spinning around it, what then causes the centrifugal force that drives the water up the inside?

The answer is truly breathtaking. We expect that the stationary water would be set in motion because all the mass-energy in the universe collectively drags spacetime around with it as it spins. This is an effect first deduced from general relativity in 1918 by Austrian physicists Josef Lense and Hans Thirring, known variously as *frame-dragging* or the Lense–Thirring effect. The possibility of frame-dragging means that there really is no measurement we can make that would tell us whether it is the water that is rotating in a stationary universe or the universe that is rotating around a stationary bucket of water. The rotational motion of the water is relative.

On 24 April 2004, an exquisitely delicate instrument called Gravity Probe B was launched into polar orbit. The satellite housed four gyroscopes whose orientations were monitored