Relativity Explained

(without maths)

Behind the curtain of reality

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For my parents Viviane & Henri
who made me curious about the world

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Chapter

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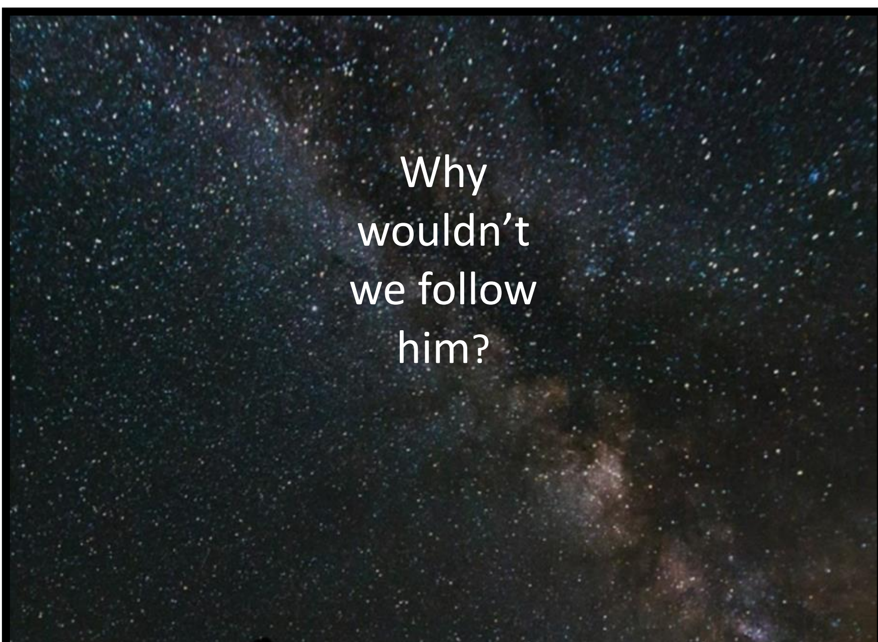
To Peek Behind The Curtain Of Reality

The magician has finished her act, you are amazed. She invites you backstage, behind the curtain, where she will reveal the secret. Why wouldn't you follow her?

We wander through our lives certain in our belief that we occupy space and that time passes. Much as we occupy a room and watch the hands of the clock on the wall mark the passage of time.

Enter Einstein, the magician's assistant, who reveals that this is an illusion - that we have all been fooled. He entices us backstage saying that everything we see and touch, every force we experience, everything including the illusions of space and time themselves are all woven from the same thread, that our reality is not the reality.

And with that he disappears behind the curtain.



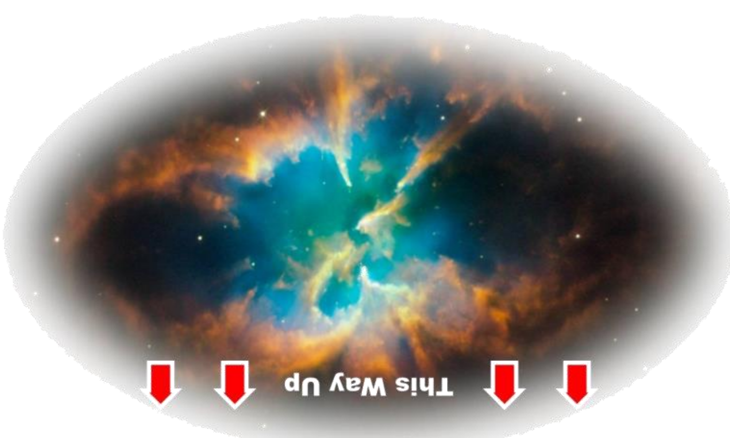
Einstein's Legacy

Upon publishing his theories of Relativity Einstein made a number of predictions. They have all been proven. The last of these, that waves of gravity cause space and time and indeed matter itself to ripple, was proven in 2016.

The highly sensitive equipment which detected these so-called 'gravitational waves' opens a whole new field of astronomical observation. Over the last 100 years, ever more powerful telescopes using light or radio waves have revealed galaxies and exotic cosmological objects we scarcely imagined before. And now gravitational wave 'telescopes' will do likewise. This is Einstein's legacy, his final gift. It will enable us to peer even further behind the curtain of reality.

A child-like question – A universe-shattering answer

Albert Einstein was 16 years old when he first wondered how the universe would look if he could ride on a beam of light. This is the story, the explanation, of how that simple question eventually revealed a startlingly different universe to the one we believe we inhabit.



The universe is not as it seems

THIS SMALL BOOK IS FOR YOU IF ……

… any of the following applies. You …

- want to understand Relativity - without any mathematics,
- feel that books with appealing titles such as 'Relativity made easy' have been written by brilliant minds which understand their subject too well, but have forgotten how hard it can be to grasp in the first place*,
- have heard the basic ideas that: nothing travels faster than light; 'space-time' is four-dimensional; length, time and mass+ change as the speed of light is approached; and that $E=mc^2$ - but you struggle to understand why these things are true or how they are all connected,
- feel that without some understanding of Relativity, its bold practical and philosophical implications lie even further beyond your disbelieving grasp, constraining your attempts to stare in amazement at our re-envisioned universe,
- feel that surely there must be a way to communicate a convincing explanation of Relativity to a layman - over just a cup of coffee, or
- just want to peak behind the curtain of reality.

* My advantage is that (a) I am not that clever, (b) I wrote this book whilst still on my own journey of discovery, and (c) this book has been expertly reviewed, see Acknowledgments on page 128.

+ Mass doesn't actually change as speed increases, it's a common misconception which is explained later.

Why Is It Useful To Understand Relativity?

There are three reasons.

Knowledge for its own sake

The development of human society relies on the cumulative development of ideas. When those ideas are wrong, we take wrong turns. When they are right, we advance. The more we know, the better we become.

Building the future

Without Sir Isaac Newton's earlier explanation of gravity and motion vast swathes of currently useful technology would not have been possible; from aerospace to biomechanics to construction and beyond. Tomorrow's scientists and engineers, inspired by today's knowledge, will be better placed to build a better world.

Who we are and what sort of world we live in

There is no absolute necessity to understand anything, but we do attach more importance to some things than to others. How to avoid getting run over is high on the list of what to teach children. Also high on that list is some sense of who we are, individually and as a species. That discussion is best informed by facts.

We learned just 400 years ago that Mankind was not at the centre of the universe; and, less than 100 years ago, that there was much more to the universe than just the visible night sky. So much, in fact, that it's quite possible we're not even alone in the universe. Understandably, such discoveries have led to change in our primitive ideas of who we are. It wasn't wrong for early Man to think himself the centre of the universe. It fitted the facts then available. But it was wrong that belief systems based on those primitive ideas proved unshakeable despite contradictory evidence for far too long.

Through Relativity our awakening continues.

RELATIVITY: FAR-REACHING BUT LITTLE UNDERSTOOD

Relativity's profound implications are at least as important as the Theory of Evolution to humankind's sense of the world and our place in it. Despite this, it remains little understood.

Unlike googling 'define evolution', the search 'define relativity' will not yield a fully meaningful description of Relativity.

> Google
>
> **evolution**
>
> *noun*
>
> The process by which different kinds of living organism are believed to have developed from earlier forms during the history of the earth.
>
> **relativity**
>
> *noun*
>
> The dependence of various physical phenomena on relative motion of the observer and the observed objects, especially regarding the nature and behaviour of light, space, time, and gravity.

This definition of Relativity is one of the simplest you will find. Yet to the average person its real significance is obscured by a somewhat involved and scientific definition. It gets worse. Reading beyond this opening paragraph the reader will meet a very deep dive into physics.

Trying to understand Relativity can be dauntingly hard. But it need not be. It can be done with simple logic. For a proven theory with far-reaching implications it is important for an understanding of Relativity to be more accessible.

An Everyday Definition Of Relativity

This is how I would define Relativity.

relativity

noun

A proven theory which describes the workings and structure of our universe. It explains that what we observe depends on how much faster we are travelling than the thing we are observing. As such Relativity reveals a universe radically different from the one we perceive with our everyday senses.

Asked for more detail, I would say the following.

Relativity demonstrates that*:

- Nothing can travel faster than light.
- Space and time are not rigid properties; space contracts and time slows as objects approach light-speed.
- Despite perceiving space and time as separate they are in fact two aspects of a single ‘space-time’ fabric of the universe; and so, when we say that the universe is expanding, it is space-time doing so.
- Matter is made of very high density energy.
- Space-time is curved by matter or energy, and what we experience as ‘gravity’ is the result of objects responding to the slopes in space-time curves.

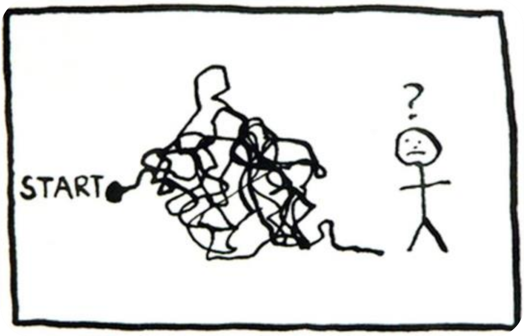
Relativity is one of the most important advances in human understanding there has ever been, making possible much new science and engineering.

Beyond science, it challenges our sense of reality and shines a light on philosophical questions about the nature of time, and on the nature of the universe and our place in it. Furthermore, in sparking imaginations it has influenced culture and society in diverse areas.

(* Don’t worry about understanding or believing this list for now - explaining it all is what this book is about.)

UNRAVELLING RELATIVITY

This book aims to unravel the mystery of Relativity in the most straightforward way possible. Before we start we'll highlight a few things which will help.



1 Historical context

Awareness of the historical context from which Relativity emerged greatly assists understanding. Physicists have been trying for centuries to understand the workings of the universe. Generally that understanding progresses one small step at a time. Occasionally there is a major breakthrough, such as Relativity, but it is not wholly disconnected from what went before as we shall see.

2 Logic, pure and simple

It is possible to appreciate Einstein's Relativity with little or no mathematics and without, for some of us, its suffocating rigour.

There are physicists who believe that it's not possible to appreciate the meaning and beauty of modern physics without some use of mathematics. This seems all the more ironic given Einstein's own use of logic. It was from his so called 'thought experiments', simple and some even fun, that he developed his initial ideas; which he *then* underpinned with mathematics.

In similar vein, I would argue that we can appreciate a cathedral's beauty without understanding the complex engineering maths behind the elegant but seemingly implausible columns supporting equally implausible vast vaulted ceilings. A simple explanation enhances our marvelling at the graceful power.

Of course, with a deeper understanding of the architect's calculations comes a deeper appreciation of the art of the architect and what he or she has achieved. But it is not a prerequisite to any appreciation at all. When describing the cathedral to friends, we don't roll out its blueprints. We use words and pictures to describe the vaulted ceiling's scale and beauty. If asked, we'll describe how an arch can support far more weight than a flat ceiling but draw short of the mathematics which explains that technology.

It is the same with Relativity. Logic is all we need to gain some appreciation of the beauties of the laws of nature.

Einstein wasn't *impossibly* clever

Mere mortals find it hard to grasp
The quite surprising thought
Of Space and Time Equivalence
Across universe so vast.

And yet the maths it so decrees
The science proves it true
So we assume its inventor's
Brain, As large as planets be.

But for us who are not built the same
How to grasp what he declared?
To peer behind his hair and maths
With a logic more mundane?

3 Simple concepts about travelling from A to B

There are just a few simple concepts which we'll need in this book.

How quickly I can sail from A to B depends on a number of factors. These include my speed and direction of travel and whether I encounter assistance or resistance.

The faster my speed, the more quickly I travel the distance

Speed is measured in 'kilometres per hour' (km/h) or similar. If I sail 4 kilometres (km) in 1 hour my speed is 4 km/h. If I double my speed to 8 km/h I'll cover the 4 km in half the time, i.e. 30 mins. In other words:

SPEED equals DISTANCE divided by TIME

$$\text{or, speed} = \frac{\text{distance}}{\text{time}}$$

(In this book, the words 'distance' and 'space' are used interchangeably to mean similar things, depending on context.)

Direction matters

If I take a zig-zag course from A to B, it will take more time than a straight line course. In other words, direction of travel is as important a consideration as speed of travel.

Friction-free travel

Throughout this book, in all the examples and explanations, a simple assumption is made. When we talk about objects or light waves travelling anywhere, we assume they are doing so in a vacuum. They aren't stopped or slowed down by anything, unless stated.

That's just the normal convention used by physicists (except of course when they're actually trying to understand how air resistance, friction, etc. affects motion).

4 Challenging preconceptions: Seeing should not limit believing

Our own everyday perceptions of the world are what most inhibit our understanding of Relativity. For example, we will discover that if we travel very very fast time appears to slow and length contract. Every fibre of our being rejects what it believes to be this obvious nonsense.

That's how we humans are wired; evolved to subconsciously make sense of our surroundings based on our everyday experience. But we don't actually have any experience of travelling at vast speed; one *million* times faster than an aircraft. So as you read you will need to distrust your reactions if they are actually based solely on what you had unconsciously presumed to be right.

Imagine you were born and raised on a very large plain. Gently rolling fields of tall grass and trees swaying in the breeze are all that you can see. One day a stranger visits with tales of mountains taller than the sky and oceans of water bigger even than the plain you're standing on. Of course, you're incredulous; maybe even you disbelieve the stranger. But what right do you have to be so sceptical - just because all that you've ever seen is a gently rolling plain?

> The highest form of ignorance is when you reject something you don't know anything about.
>
> *Wayne Dyer, Philosopher and author*

WHAT TO READ

This book is organised as follows. The explanations of Relativity are in three progressively more detailed chapters.

- *Relativity Over A Cup Of Coffee*. This may satisfy your needs, or it may serve to ease you into the next chapter.
- *More Detailed Logic*. If you want deeper explanations. You can jump straight to this chapter if you wish, but it may well be useful to read the *cup of coffee* overview first.
- *A Little Bit of Maths*. Purely optional maths, if interested.

In addition there is a discussion about Quantum Mechanics and how it and Relativity contribute to the on-going search for a 'Theory of Everything'. And there are less technical chapters: physical evidence that supports Relativity theory; its implications for our understanding of time and other philosophical questions; its influence on culture and society; and a chapter on Einstein himself.

DON'T BE PUT OFF

As we'll see logic is all that's needed to explain Relativity. However, understanding it is not all plain sailing. Relativity encompasses many broad and very challenging concepts. Don't be put off. It may well not all fall into place in one go. Keep going - you will almost certainly gain a better understanding than before you started.

I hope you enjoy the journey.

> Relativity 'appealed to me like a great work of art … the greatest feat of human thinking about nature, the most amazing combination of philosophical penetration, physical intuition, and mathematical skill [even though] its connections with experience were slender.'
>
> *Max Born, Nobel prize winning physicist*

Chapter

RELATIVITY OVER A CUP OF COFFEE

This chapter explains Relativity in three steps.

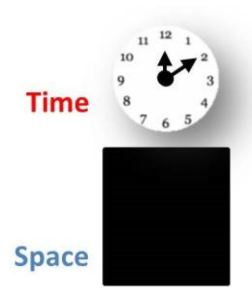
1 Showing how our everyday ideas of space and time are flawed.

2 Describing how a new 'four-dimensional' understanding of space and time addresses these flaws.

3 Describing how this new understanding leads to further insights into how the universe works.

1 EVERYDAY IDEAS OF SPACE AND TIME ARE FLAWED

A UNIVERSE-SIZED ILLUSION



Our everyday experience strongly conditions belief in two things. First, that space is a rigid unbending container. And second, that time is totally separate to space: ticking with constant rhythm throughout the universe whether we are there to observe it or not. And yet, as we'll discover, these beliefs are based only on flimsy intuition.

LIGHT-SPEED IS SUPER-FAST BUT NOT INSTANTANEOUS

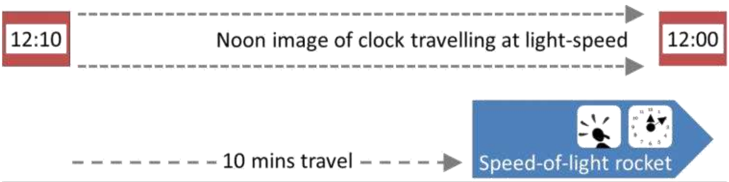
Our 'everyday experience' includes travelling at speeds we consider high, such as in an aircraft. Yet this is only *one millionth* the speed of light. Indeed light travels so fast that it takes just 1/10th of a second to travel around the earth. As a result we've evolved to believe that everything we see is happening 'now'. But light is not infinitely fast. For example, it takes 8.5 minutes to reach the earth from the sun.

So it seems reasonable to ask if our intuition of space and time would be different if we travelled at enormous, light-like, speeds. By asking this simple question, Einstein made profound discoveries about how our universe works.

It's Time ... But Not As We Know It

Imagine that you are alone in a rocket in deep space beside a digital clock. At 12 noon you travel slowly away from the digital clock. After 10 minutes the rocket's clock shows 12.10. You look at the digital clock. It too shows 12.10. So far so good.

You repeat the experiment, this time travelling at the speed of light. After 10 minutes the rocket's clock shows 12.10. Back at the digital clock, it too probably shows 12.10, but you can't be sure. Its 12.10 image is only just leaving its clock face. What you see outside your window is its noon image which has also (of course) travelled at the same light-speed, beside your rocket. (This *thought experiment* is not invalidated by the real world impossibility of light-speed travel.)



> That's it! That's the Theory of Relativity! Light travels to us from the face of a clock, to tell us the time. But, if we travel away from the clock at the speed of light the face of the clock appears to have stopped! Time would stand still. This moment would last forever.
>
> *Fictional dialogue between Albert Einstein and Marie Curie*
>
> *Adapted from the movie: Young Einstein*

Which do you trust? Is the rocket's clock fast or has the digital clock stopped? To check, you look for the universe's master clock and realise there is none to which you can refer. You conclude that:

- It is not necessarily the same time everywhere.
- You're looking at the digital clock's *past* outside your window - despite everyday belief that we observe events in the *present.*
- It follows that if you could travel faster than light you'd catch up with events from before you even started your journey!
- The time difference you perceive between the two clocks depends on the rocket's speed.

It's Space … But Not As We Know It

If everything is so dependent upon the rocket's speed, we'd better take a close look at how we're measuring that.

We left the rocket moving away from the digital clock at the speed of light. But how can we be sure that the rocket isn't stationary and the digital clock moving; or indeed both moving away from each other? It is like watching one moving train from another: is that train moving forwards or is your train moving backwards? You can only be sure by checking your surroundings. But in deep space there is no unique reference point by which all motion can be compared. (Stars can't help. Like your rocket, they are just objects floating in space.) There is no absolute way of knowing which one (or both) of you is moving. You can only be certain of the **relative speed** difference between you and the digital clock.

In Summary, Clearly Flawed Ideas of Space And Time

Everyday experience leads us to expect that there is a unique point from which to measure motion, and that time is absolute. We don't actually have any proof, we just allow our intuition to prevail. But, motion and time can only be measured relative to other objects.

We've seen that by the time light from an object reaches us we are seeing an image of its past, not its present as we tend to think. In other words, we see images of 'now' and 'then' from a point in time just as we see images of 'here' and 'there' from a point in space.

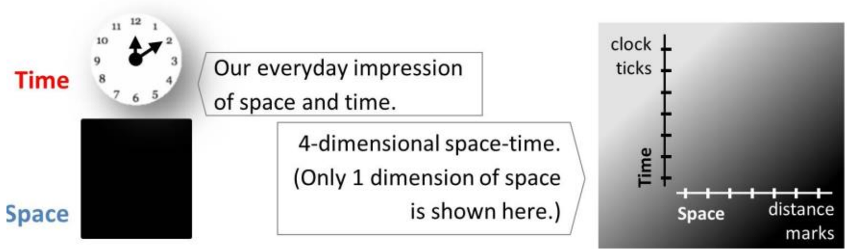
This is so very different from our beliefs that it's worth taking a moment to absorb it fully. Our impression of space and time is flawed, they are not rigid and absolute. We are now ready to meet the stranger with tales of mountains higher than the sky and oceans of water bigger than the plain on which we stand.

2 A NEW UNDERSTANDING OF SPACE AND TIME

GOODBYE 'SPACE' AND 'TIME' … HELLO 'SPACE-TIME'

Given the similar characteristics of 'space' and 'time' we've just summarised, perhaps they are actually more similar than we tend to think. It suggests an alternate design of the universe, one better able to express these similarities.

Instead of three dimensions (3D) of absolute space (up/down, side-to-side, forwards/backwards) and a separate constant rhythm of time, perhaps they can be regarded as a single four-dimensional (4D) fabric, 'space-time'; a fabric without any unique universal reference point.



We don't perceive 'time' as we do 'space' because, as low-speed 3D humans, our senses have evolved according to our needs. Since we don't travel at anywhere near light-speed we're totally unaware of the flaws in our old ideas. But as relative speed approaches light-speed, these differences become significant.

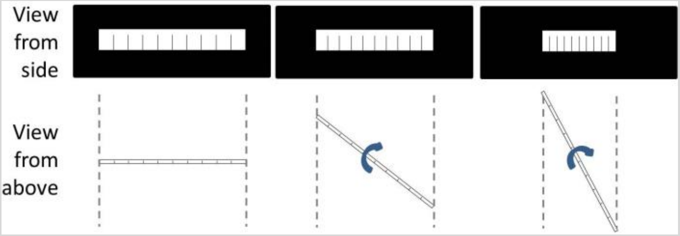
Furthermore, as we have said already, we can only ever be certain of the relative speed difference between us as observers and the objects we observe. So, in our earlier example, an observer standing by the digital clock would have much the same difficulty as the astronaut in knowing the right time. Each observer observes the other from their own 'bubble of reality', and that is hugely significant as we are about to discover.

MOVING THROUGH SPACE ***AND*** TIME CHANGES PERCEPTIONS

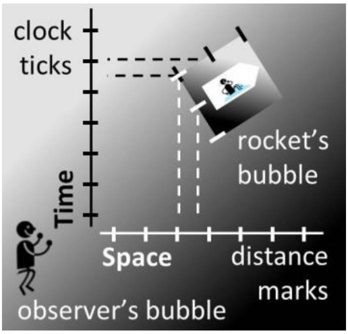
Our everyday idea of movement is that objects move through 'space' in a given period of 'time'. But the 4D fabric of 'space-time', shown in the previous graphic, implies a subtle but important difference: that as objects move through space they are also moving through time. The analogy in the box below explains why this is important.

Challenging preconceptions: the limits of our senses

A white ruler is suspended against a black screen. As we watch from a distance the ruler appears to shorten. When viewed from above, we learn the truth. The ruler is moving in two space dimensions (side-to-side and front-to-back), but we're initially only aware of side-to-side changes. The white on black contrast hinders our sense of depth.



As with the ruler analogy we low-speed humans, though moving through space *and* time, only see the dimensions of space. We've not evolved to see the time dimension in the same way: it's effectively hidden from our senses. Only by travelling at vast light-like speeds does the implication of moving through space *and* time become apparent. A 'stationary' observer perceives that a fast-moving rocket is shorter than she expects and its clock ticks more slowly than hers. The diagram at right represents this 4D reality, though it's just a representation of something we can't actually draw.



Of course, when the rocket slows down, relative differences become negligible again. But in the meantime, by comparison to the observer, the rocket's clock has forever lost seconds it cannot regain.

MORE ON LENGTH CONTRACTION AND SLOWING TIME

There are some things to know about these effects.

(1) We all believe that our own rulers and clocks behave normally and that it is the object moving relative to us, e.g. the rocket, for which distance has contracted and time slowed. But since motion is relative the rocket's astronaut believes the opposite.

(2) The observed length of moving objects only contracts in the direction of travel because there is no relative speed difference in other directions. So, our earlier light-speed rocket becomes shorter in length but remains the same in height and width.

(3) As relative speed approaches light-speed, these effects increase exponentially. Until, at light-speed, length contracts to nothing and time slows to a standstill making it impossible to go faster.

LIGHT-SPEED, THE FASTEST THING IN THE UNIVERSE

Light- speed has been measured as 299,792,458 metres per second. We'll call that 300 million m/s from here on. But 'light-speed' is more profoundly important. Since space is empty and light has no mass, nothing slows its progress. It travels as fast as the universe allows. If a faster-than-light-signal did exist it could inform us, say, of a dropped ball on the floor before the light image of its falling reaches our eyes. But we never observe any violations of cause and effect. So we can safely presume that light-speed is the **universe's speed limit** (denoted by the letter**, 'c', for constant**).

Universal speed limit? Measured relative to what or who?

We've shown that motion is relative. So if light-speed is the universe's speed limit, we must ask, 'relative to what?' The surprising answer, proven by experiment (see page 29), must be 'everything'. All observers witness this same universal speed limit. But how can two observers moving relative to each other measure the same speed 'c' of a light beam? The answer lies in length contraction and slowing time.

$$\frac{\text{distance}}{\text{time}} = \text{Light-speed}$$

Together, length contraction and slowing time ensure the same answer is calculated by different observers for the speed of light.

$$\frac{\rightarrow \text{distance} \leftarrow}{\rightarrow \text{time} \leftarrow} = \text{Light-speed}$$

3 NEW INSIGHTS INTO HOW THE UNIVERSE WORKS

Revising The Laws Of Physics

We’ve seen that observed ‘distance’ and ‘time’ vary with relative speed. But these properties of Nature are fundamental to the laws of physics. So Einstein made adjustments to these laws to allow for those variations, and this led to further insights.

Mass Also *Apparently* Increases As Speed Increases

Relativity Theory is often alleged to state that an object’s mass increases the faster it travels. If it seems strange that an object gains extra matter just by going faster, you’d be right, it doesn’t.

What the object does gain is more energy. The more we push it the faster it travels and the more destructive energy it has when it collides with another object. (This is called **momentum**.) The faster an object travels the harder it also becomes to deflect it from its course, *as if* it had gained mass. That much is normal physics.

At very high speeds this observed gain in momentum is accentuated by slowing time. And as the object’s speed approaches light-speed its momentum approaches infinity, making it impossible to change its course or speed at all. That’s why objects with mass cannot be made to travel faster than light-speed.

The Relationship Between Matter And Energy, $E=mc^2$

Physicists already knew there was a relationship between matter and energy: decaying radioactive atoms lose mass and release radiation (i.e. energy); but had no idea what the relationship was.

Even before Einstein it was known that light energy travelled as a wave: think of rainbows where each colour is light of a different wavelength. Separately, Einstein had proven that light, in the form of tiny packets of energy, also behaves like particles. (He’d used this to explain the phenomena of photoelectricity.) He showed that in collisions these particles behave like snooker balls, i.e. like matter.

If light can take the form of wave energy *and* of matter particles Einstein reasoned that there must be some **equivalence between mass and energy**. He discovered that this relationship was given by $\mathbf{E=mc^2}$ (where 'E' is energy, 'm' is mass, 'c' is the speed of light, and 'c^2' means 'c' times 'c'). Since 'c' is a very big number, so 'c^2' is huge, and the energy in even a tiny amount of matter is vast.

The simplicity of the equation $E=mc^2$ also points to something else. Since matter and energy are related, purely and simply, by a constant 'c^2', then what we perceive as solid matter is 'nothing more than' very densely packed energy. And, given that that's the case, it suggests that matter can be converted *completely* into energy. This is what lies behind the opportunity and threat of nuclear reactions.

How much energy is there in a rugby player?

An average-sized 100kg male rugby player fully converted to energy through a nuclear reaction would meet the UK's annual energy demand. If instead the unfortunate rugby player was burnt on a fire (a chemical reaction) he'd barely warm a family for an evening. (See *A Little Bit of Maths* for the calculation.)

NB Nuclear reactors convert only a fraction of matter into energy.

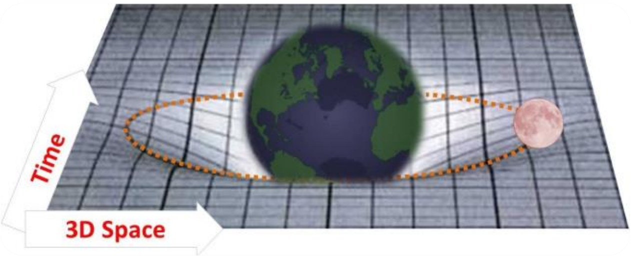
REVISING THE LAWS OF GRAVITY

In 1687, Sir Isaac Newton published equations describing how the force of gravity acts. They worked brilliantly for everyday speeds. Despite this, Newton did not know what gravity actually was.

Einstein realised that our experience of gravity is indistinguishable from our experience in a rocket that is increasing in speed, the pressure felt between feet and floor is the same. In just the same way that we feel heavier in a lift as it starts to rise.

Perhaps, he wondered, gravity is 'just' our experience of some change to our speed or direction. But if so, what gives rise to that change?

In the graphic below space-time is depicted as a 2D grid painted on a rubber sheet. The presence of a mass causes space-time to curve, as shown. This in turn supports the object in that position.



The analogy of a boat in water may help. When in the sea, the boat displaces water. In turn, the weight of displaced water pushes back creating what the object experiences as buoyancy.

These 'curves' in space-time influence nearby objects to be drawn towards the larger object; much as a person lying on a mattress creates a 'well' towards which their partner rolls. It is this which we experience as gravity. And the bigger the central mass, the greater the influence on nearby objects will be.

THE SPEED OF LIGHT 'C' IS REALLY VERY SPECIAL

We've seen that light-speed, the universe's speed limit, defines the relationship between space and time, and between mass and energy. As such, it is fundamental to the universe's design and operation.

It turns out that the universe is not defined by rigid space and absolute time in the way we perceive. Rather, it is rigidly defined by a universal constant 'c', the speed of light.

It is as if 'c' allows us to peer deep into the design of the universe; a step on our journey '*to know the mind of God*,' as physicist Professor Stephen Hawking put it.

It's Not All Relative

The laws of physics utilise fundamental properties such as 'distance' and 'time' in equations to describe how our universe works. These *laws* are the same throughout the universe.

However, the *values* we measure for these fundamental properties are 'relative'. They vary depending on how an observer, moves *relative* to the objects observed. Hence the name, Relativity.

How To Appear Slim And Stay Young Looking

If you have the means to travel at near light speeds Relativity provides a surefire way to appear comparatively svelte and young. But, only as long as your friends aren't travelling with you. If they are the lack of relative speed difference means it wouldn't be much of a 'comparative' experience!

So if you do choose the high speed travel option to looking in ruder health than your friends, you'll have to do so all alone. And, because motion is relative, when you look at your friends, you will think they look in better health than you!

Congratulations!

Understanding Relativity can be challenging, but hopefully you've had the opportunity to appreciate the beauty of the laws of nature.

By way of a summary you may wish to return to the description of Relativity on page 9.

The following quote reminds us all that our intuition is not the most reliable guide to how the universe beyond our everyday experience actually works.

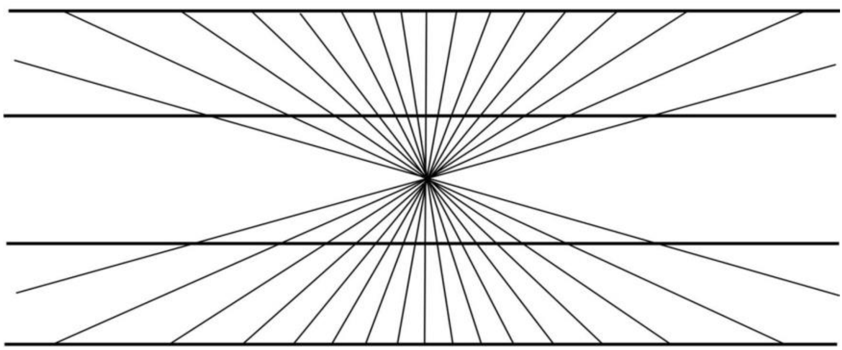
> "The universe is under no obligation to make sense to you."
>
> *Astrophysicist, Neil deGrasse*

NOW THAT YOU'VE FINISHED YOUR COFFEE

CHALLENGING PRECONCEPTIONS: REALITY IS NOT WHAT IT SEEMS

It's a surprise to discover that our age-old impression of space and time is based solely on our evolution-constrained senses. Do length and time really change with speed? Yes!

Of course, Relativity challenges our intuitive sense of reality. But intuition is not a reliable guide to scientific reality. It is as if our observed reality is just a universe-sized illusion.



Only straight lines are used
in this illusion of curved lines.

Furthermore, Relativity has been proven, see the chapter *Where's The Proof?* This includes examples of how Relativity theory enables the building of practical machines.

And that's the ultimate test of any theory, whether it works or not. In its day-to-day work, Science is not a quest for truth but a quest for ever-evolving theories which explain, with increasing accuracy, how the world works.

The logic of this chapter is explored more deeply in the next, *More Detailed Logic*. But if this explanation has been sufficient for you then skip that chapter and go on to read how Relativity has informed or influenced the on-going search for a Theory of Everything, our understanding of time and other philosophical questions, as well as influenced culture and society.

Chapter

MORE DETAILED LOGIC

This chapter explores more deeply the logic summarized in the previous *cup of coffee* length description of Relativity. Although that chapter is not required reading before this one, you may find it helpful to have gained that overview first. This chapter is organised as set out below.

1 Before Relativity

'Classical' physics had been working so well.

2 Simple yet profound questions

Reveal flaws in the classical theories.

3 Time slows and space contracts

As speed increases. Strange but true.

4 A radically new view of the universe

Goodbye space and time. Hello space-time.

5 Revising the laws of physics

New perspectives on matter, energy and gravity.

6 Insights into the universe's design

An expanding universe. Defined by the speed of light.

7 And finally

A few loose ends.

A Few More Concepts About Travelling From A To B

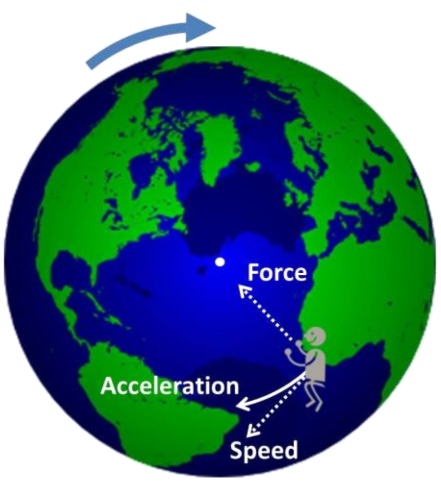
Before we continue however, we need to add a few more concepts to those on page 12. Don't worry if you don't understand them fully now.

Changing speed or direction: 'Acceleration', 'Force' and 'Mass'

If I change speed or direction it affects how quickly I travel from A to B. Physicists call any change to speed or direction or both '**acceleration**' (despite our everyday use of the word referring only to change in speed).

To change speed or direction requires a '**force**', such as the wind. If I'm in a boat I know that the heavier my boat the more force is needed to make it accelerate. The boat's weight is, in turn, an expression of how much matter, or '**mass**', it is made up of.

There is one more thing: understanding acceleration and force in the special case of rotating objects.



Rotating objects

Consider an object on a spinning disc or sphere, e.g. *you* standing still on earth.

You feel you're not moving because your speed is zero *relative* to the earth. But, as you travel in a curved path, you're constantly changing direction, and therefore *accelerating*, according to the definition of acceleration.

The definition also says that for a mass to accelerate there must be a force. In this case, the 'force' is provided by gravity, preventing you from being thrown off the spinning earth and travelling out into space in a straight line.

1 BEFORE RELATIVITY

GALILEO, NEWTON AND MAXWELL

In 1632, Galileo Galilei considered a sailor in a windowless cabin of a ship on a perfectly calm sea. He said the sailor would be unable to tell if his ship was stationary or moving 'uniformly', i.e. with constant speed and direction. Even if we gave the sailor a window from which he sees another ship appearing to sail past, he would have no way of knowing which ship, his or the other (or both) was actually moving.

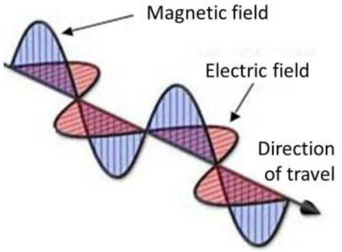
Furthermore, whether the ship is stationary or moving with constant speed and direction, a ball thrown straight up into the air would fall straight down, back into the hand which threw it. If it did not Galileo's sailor could use this information to understand if his ship is moving or not. (Only if the ship changes speed or direction would the sailor observe the ball falling away from his hand.) This is known as the '**Principle of Relativity**': Galileo's sailor can only describe his position or motion *relative* to other objects, and not by reference to any absolute reference point.

Then, in 1687, Sir Isaac Newton explained how the universe worked. His theory combined motion on Earth and in space into a single working model which matched observations and predicted events. This brilliant model of the universe, accepted the Principle of Relativity. It also presumed that space (i.e. distance) was rigid and that time was absolute. Newton's universe marched to the beat of the same clock everywhere: a rigid clockwork mechanical universe.

Cracks in physics #1

Newton's theory seemed to explain everything people saw and could make accurate predictions based on calculations. So far, so good. But if there was an absolute universal clock ticking away somewhere by which to measure time, Newton's theory did not explain how it operated. By not making any progress toward answering the question 'what is time?' his theory was incomplete.

In 1861, James Clerk Maxwell explained that electricity, magnetism and light were not separate things, as we perceive them, but are in fact all aspects of the same phenomenon called 'electromagnetism'. Maxwell also showed that light was an **electromagnetic wave** and explained how it travelled. In daily life we use such waves all the time, e.g. mobile phone signals and wi-fi.



Light is an example of an electromagnetic wave. These waves are self-propagating: the vibrating electric field stimulates a magnetic field (at right angles to it) and vice versa. And, unless obstructed in some way, there is nothing to interfere with this continued action.

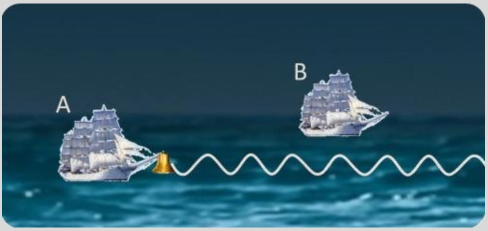
Maxwell's theory gave the speed at which electromagnetic waves such as light travelled. And many experiments came up with the same answer for the speed of light. Einstein said of Maxwell's work that, '*This change in the conception of reality is the most profound and the most fruitful … since the time of Newton*.'

The fact that Maxwell had proven that light was a wave, an electromagnetic wave, was good news. Physicists understood waves such as ripples *in water* or sound *in air*. The question they turned their attention to now was, light in '*what*'. And so the search for the 'what' started; a search for a concept first suggested 200 years earlier by Christiaan Huygens, and which he'd called the '**ether**'.

Cracks in physics #2

In 1887, an experiment by **Albert Michelson and Edward Morley** surprised the scientific world. They'd set out to find evidence for the ether. In their experiment a light beam was split in two. Each half was sent in different directions (at right angles to each other), reflected back, and then compared in a detector to see if their wave peaks and troughs still coincided. The speed of rotation of the earth should have been sufficient to change the wavelength of the beam aligned with the earth's rotation while the other remained unaffected. And yet no such effect was observed. They concluded that an observer will always observe the same speed of light relative to him, no matter how fast he is moving. This is known as the '**invariance of the speed of light**'.

By way of analogy, consider the situation at right. The sound waves from the bell on ship 'A' travel out in all directions. One sound wave is shown by the white line. Imagine that Ship 'A' is super-fast and can sail faster than sound. It arrives in port before the harbour master hears the ship's bell. So we can say that ship 'A' notes the sound wave is travelling more slowly than itself, while 'stationary' ship 'B' notes the sound wave travelling at normal speed. That all makes sense. The problem arises if, instead of a ship's bell, we have a ship's searchlight. In this situation, the 1887 experiment showed that no matter how fast ship 'A' travels it could never catch up with the light beam, let alone overtake it. Not only that but, observers on ship 'A' would always measure the light's speed as 'light-speed' faster than their ship; no matter how fast or slowly ship 'A' itself was travelling. And yet, despite this, observers on ship 'B' would continue to measure the same speed for the speed of light relative to their ship.



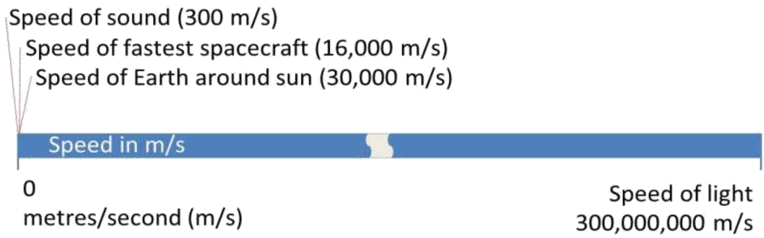
This experiment also hints at the further conclusion that nothing can actually travel faster than the speed of light. All this was impossible to explain using any known physics. There was no precedent for this with any other type of wave.

CHALLENGING PRECONCEPTIONS: EVERYDAY SPEED V LIGHT-SPEED

The speed of light was first measured in 1676 and shown to be finite but exceptionally fast. So fast, that on our relatively small earth we're conditioned to believe that all we observe is happening 'now'. In actual fact as we look at distant objects we see them as they were when the light that has just reached us, left them: we're seeing their 'past'. This is just one example of how our intuition fails us.

Furthermore, we only know through experience how the world works at our everyday low speeds of travel on earth. We don't actually know what happens to objects as they travel at *one million* times our everyday experience. It seems sensible not to presume.

For example, we wouldn't take just one millionth of the Bible's 750,000 words and pretend to understand Judaism and Christianity.



Physics, Job (Nearly) Done?

Newton's and Maxwell's brilliant theories served to unify features of the world we observe. Newton: motion of objects in space and on earth. Maxwell: electricity, magnetism and light.

Newton, 1687
Gravity (*motion in space & on earth*)

Maxwell, 1861
Electricity
Magnetism
Light

It spurred physicists to wonder what else could be unified. At first glance Maxwell's work seems to have nothing to do with Newton's. But if physicists could find the universal ether which carried light waves, maybe it would turn out also to be the structure underpinning Newton's rigid mechanical universe.

Despite this search for the ether and the highly surprising Michelson-Morley result, and despite the unresolved question 'what is time?' we might forgive physicists of the very late 1800s. Having found theories for all then known forces and types of energy (including heat, see Thermodynamics on page 89), there were a small number who expected that all that was left was some fine tuning of their theories before being able to declare 'job done'.

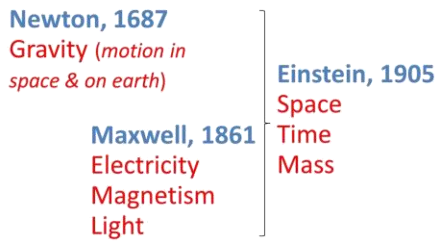
There were just two problems. Firstly, the question, 'what is time?' was about to reveal glaring problems, as we'll see shortly.

And secondly, the atom was about to be prised open up for the first time and its inner workings would reveal new nuclear forces. These nuclear forces would also be important to understanding how the universe works. (These inner workings of matter are described briefly in the later chapter *Theory of Everything, Quantum Matters*.)

2 SIMPLE YET PROFOUND QUESTIONS

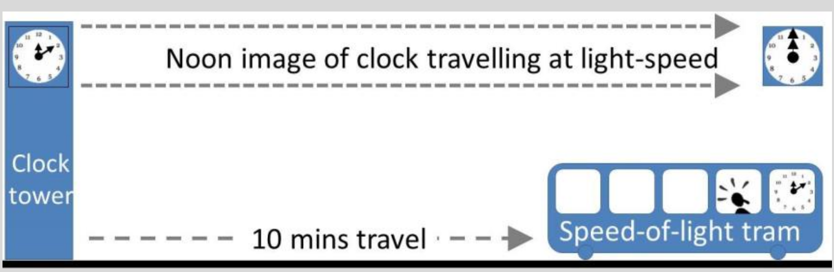
ENTER EINSTEIN, TRAVELLING ON A BEAM OF LIGHT

Einstein first started having doubts about 'space' and 'time' in 1895 at age 16. He asked himself how the world would look if he could travel on a beam of light. He couldn't have known that this simple question would unlock a completely new view of the universe; or that it would unify many of physics' existing theories and thereby put him on a par with Newton and Maxwell.



Thought Experiment #1: Travelling at the speed of light

Einstein was still grappling with this question in the early 1900s. Each day he boarded a tram to go to work at the Swiss Patent Office in Bern. He imagined his tram travelling at the speed of light away from a clock tower, starting at noon.* (Of course, we now know that nothing can actually travel at the speed of light. But in the early 1900s, before Relativity, the classical view of physics ruled. It was classical physics' assumptions that Einstein was putting to the test here.)



Einstein realised that as he sat on the tram looking out of the window the tower's clock would appear frozen in time, at 12.00, because both he and the light of the noon image are travelling at the same light speed. He also realised that the tram's clock would be ticking as normal, so after 10 minutes it would read 12.10!

(* Despite this story about Einstein being widely and reputably used, there is evidence it is a myth. Nonetheless, no one doubts its scientific validity.)

Tram-riding Einstein has a problem: how to know the right time? Perhaps this is just playing with logic, some sort of trick.

But now imagine a stationary pedestrian, let's call him Newton. He observes the tram as it shoots past at the end of this 10 minute period. Newton believes that time is absolute. It marches to the same rhythm everywhere in the universe. And he believes that, by whichever means the universe came into existence, it did so at the same time everywhere; and that, ever since, time has ticked away at the same rate everywhere. So Newton believes (in fact he believes he *knows*) that when it is 12 noon at the clock tower his wristwatch must read 12 noon too. He doesn't know how the universe makes this happen, but it is, according to Newton's theory, how the universe works.

Newton is therefore delighted when he sees the light of the clock tower's noon image arrive, as far as he is concerned, bang on time. He is, however, appalled to observe that the tram's clock reads 12.10. The tram's clock and the clock tower's image have travelled the same distance at the same speed, and yet Newton observes contradictory times.

This is clearly not a trick. It is an issue demanding a serious rethink.

Once again, Newton's presumption of absolute time appears problematic. How can tram-riding Einstein or our by-standing Newton know the actual time? Is there even such as thing as the universally agreed 'right time'? This exposes the underlying question: if Newton is right, then how does this universally agreed time make itself known everywhere? Einstein went further: can clocks in different locations be synchronised, so that there can be universal agreement about the time? (We'll see later, on page 37, how Einstein showed that they can't.)

This thought experiment also highlighted another very important point. There appears to be some sort of relationship between the speed of light and time itself. Such a relationship would be an enormous blow to the idea of absolute and universal time.

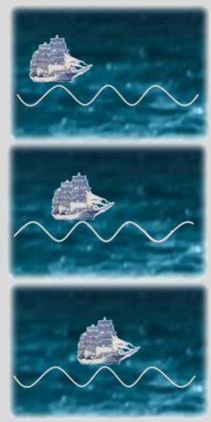
Cracks in physics #3

The ‘riding a beam of light’ question is quite simple to ask but enormously profound in its implications.

If it were possible to travel at light-speed alongside an electromagnetic wave of light, we would be keeping pace with a peak or a trough or some other point on the wave. So we would not see or experience the light wave’s energy. To us, it would be as if there was no wave and so it would appear unable to transfer its light energy from one place to another. The analogy below might help.

The ship on the left is stationary. The ocean’s waves are moving from left to right as shown by the floating barrel. So the wave’s energy bobs the ship up and down.

The ship on the right is moving at the same speed as the wave. To its crew, the wave appears stationary and without any energy as the ship rides the crest of the wave.



So, returning to Einstein’s question, as we travel alongside the light beam, it would appear not to be travelling anywhere, let alone shining. But, to a stationary observer, that very same light wave would continue its illuminating journey. Much as if we are sitting on the hour hand of a giant faceless clock as it slowly sweeps time we wouldn’t perceive it moving. And, with no other absolute reference points, it would appear stationary and we’d believe that time itself had stopped.

WARNING

The next nine pages are the hardest bit of Relativity. *Not* that they’re hard to understand, just hard to believe.

SOMETHING'S GOT TO GIVE

The various 'cracks' in Newton's theory revealed a tension between two concepts, seemingly incompatible within a single working model of space, time and light.

The invariance of the speed of light	*versus*	**Newton's model of rigid space and absolute time**

Newton's theories worked, but only *almost* perfectly. And there was actually no certainty that space and time were rigid or absolute. This was just a very understandable human presumption.

On the other hand, Maxwell's electromagnetic wave theory of light worked perfectly. Importantly, its equations supported the idea of the invariance of the speed of light. So Einstein's concerns about travelling at light-speed and the conundrums this raised about time pushed him to conclude that something in Newton's model had to give.

It was here that Einstein made a conceptual leap. The problems could be avoided, he realised, if observers can't actually travel at the speed of light.[1] Maybe light-speed was the '**universe's speed limit**' as he called it, in a sense its 'infinite' speed. (We'll justify this notion shortly.) Now, just as the number 'infinity' is always infinitely bigger than whatever number we might think of, he suggested that no matter what an observer's speed is, she will always see light travelling at this 'infinitely larger' light-speed faster than herself. (Just as the Michelson-Morley result had demonstrated.[2]) The speed of light was a new '**constant**' of physics, denoted by the term 'c'.

[1] Bear in mind that not only was Einstein working this out before it was known that objects can't travel at light-speed, it was he that came up with the idea!
[2] Einstein said later that in 1905 he was unaware of the Michelson-Morley result. This seems likely since he'd otherwise have used it to support his assumption.

3 TIME SLOWS, SPACE CONTRACTS & 'MASS' INCREASES

The Starting Point Of Relativity

The conundrums posed by riding a light beam and the light-fast tram ride, led Einstein to the starting point from which he developed Relativity. Physicists like ideas which are simple and elegant. What could be simpler than the starting point Einstein chose? He called these his two postulates.

First Postulate

The speed of light (in empty space) relative to any observer has the same value, no matter how those observers are moving relative to the light beam itself.

In other words, Einstein is taking the invariance of the speed of light as a given, stating that it is a universal law.

Second Postulate

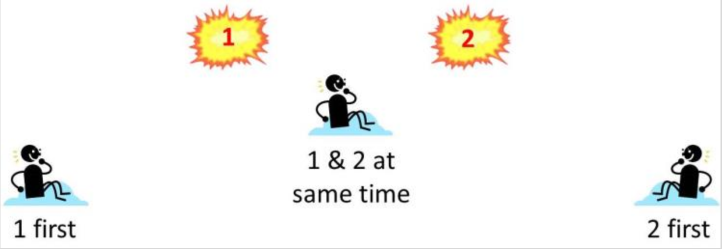
The laws of physics operate in the same way everywhere, irrespective of relative motion.

In other words, the Principle of Relativity. But here, Einstein is not only reasserting the Principle of Relativity he is extending it to apply to all moving objects, not just to those moving at everyday speeds. This therefore includes very fast-moving electromagnetic waves. That is why his first paper on Relativity was actually called 'On the electrodynamics of moving bodies'.

Thought Experiment #2: Simultaneity and Causality

The tram-riding conundrum (see page 32-33) led Einstein to this thought experiment, and to the conclusion that Newton's presumption of absolute and universal time was wrong.

In 1905, in his first paper on Relativity, Einstein imagined two unconnected events, explosions for instance, which appear to be simultaneous to a central observer: one explosion to her left and the other explosion to her right.



Then he considered two further observers, one far off to the left and the other far off to the right. Since light from each event travels a different distance to each of the outlying observers, the events will not appear simultaneous to them.*

In order to agree amongst themselves which event came first, the observers would need to find a way to perfectly **synchronise their own clocks**. But this is impossible to do at a distance, since the finite time taken by synchronising signals to travel that distance would introduce uncertainties into any attempt at synchronisation.

So Einstein concluded that there could be no universal reference clock for time.

It also seemed to support his assumption that nothing can travel faster than light-speed, neither objects nor information about events, since we don't learn about the occurrence of events by any other means. If we could learn of events by faster-than-light means, then it would be possible for connected events (i.e. a 'cause' followed by its 'effect'), for example a javelin thrown then landing, to appear reversed to some observers: the 'effect' *before* the 'cause'. But this is something never seen in the whole of human experience.

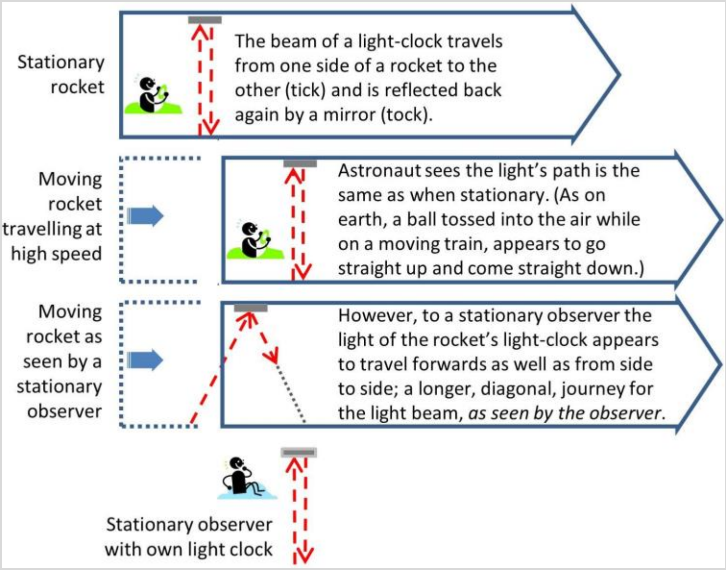
*Only if light travelled instantaneously would the situation be different. However, this isn't possible, since both Maxwell's theories and experiment (in 1676 and confirmed in 1727) had established a finite speed of light.

My Very Own Bubble Of Reality

So like Galileo's sailor in his windowless cabin we observe the universe from our own bubble of reality, our '**frame of reference**'. The *rules* of physics are the same in all bubbles; the rules which define the relationship between fundamental properties, such as distance and time; e.g. the equation for speed. But the actual *values* measured for each of these properties depends, as we see below, on the relative speed of the observers' bubbles of reality.

Thought Experiment #3: Different measurements of the same thing

A rocket astronaut and a stationary observer use a so-called 'light-clock' to measure time. Take a close look at the diagram below.



We can see that, from the observer's point of view, the diagonal trajectory of the light of the astronaut's light-clock is longer than that of her own light-clock. But light-speed is invariant: the same in both light-clocks. So the observer sees that the astronaut's light clock has not completed its longer tick-tock journey by the time her own clock has completed its journey. She concludes that astronaut time is slower than hers! Furthermore, as relative speed increases the longer the diagonal trajectory seen by the observer becomes, and the more astronaut time appears to slow to the stationary observer.

Not Just Time Slowing, But Space Shrinking

If that seems strange, there is a further surprise.

The invariance of the speed of light means that: if time has slowed, then distance must compensate by contracting so that the calculated light-speed always equals ‘c’ for all observers.[3]

$$\frac{\text{distance}}{\text{time}} = \frac{\rightarrow \text{distance} \leftarrow}{\rightarrow \text{time} \leftarrow} = \textbf{Light-speed, c}$$

Physicists call this contraction of distance, ‘**length contraction**’, and the slowing down of time, ‘**time dilation**’.

So, not only is there no absolute universal clock, as Newton’s model assumed, but length contraction contradicts his concept of rigid, absolute space as well.

Proving That Time Slows

The slowing of time has been demonstrated by experiment using highly accurate atomic clocks here on earth. (See the chapter *Where’s The Proof?* page 68, ‘experimental proof of time dilation’.)

Proving Length Contraction Is Not So Easy

It is harder to measure length contraction directly. To make such a measurement would require the remote measurement of length of something travelling at vast speeds past the ‘stationary’ observing equipment. Appropriate technology, with sufficient accuracy, does not currently exist.

However, there are other proofs of length contraction. (See the chapter *Where’s The Proof?* page 68, ‘unexpected behaviour of muons’.)

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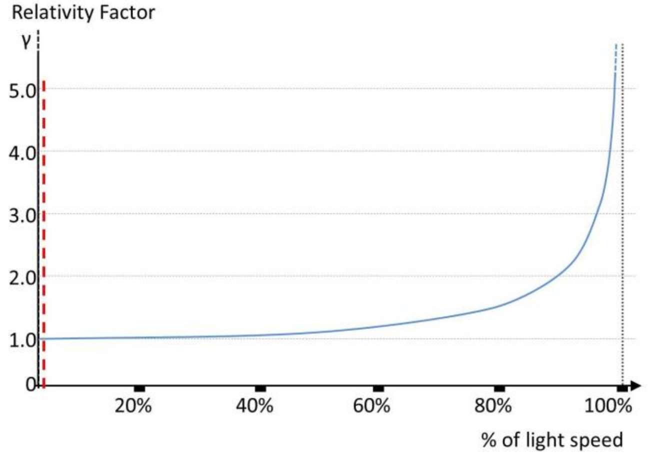
[3] It may be tempting to wonder if there is something suspect with the equation ‘speed equals distance divided by time’ itself, rather than accept that the equation implies that length contracts if time slows. However, since the equation is little more than a definition of ‘speed’, there can’t be anything suspect lurking inside it.

By How Much Does Length Contract And Time Slow?

The short answer is ‘imperceptibly’, even at speeds far beyond the everyday as the graph below shows.



The curved line in the graph shows the proportion by which length contracts and time slows as speed increases. This proportion is called The ‘**Relativity Factor**’. The world of our everyday experience lies to the left of the dotted line. No wonder we find relativistic distortions surprising!

(See *A Little Bit of Maths* to see how this ‘Relativity Factor’ is calculated using just Pythagoras’ Theorem.)

For example, at the speed of sound length contracts by just 5 millionth-millionths (that’s 5 divided by 1,000,000,000,000), something we’d never notice and find hard to measure.

Alternatively, how fast must we travel to cause noticeable length contraction, say by one thousandth of the ‘stationary’ value, so that a 1 metre ruler contracts to 999 millimetres? The ruler would need to travel at 14 million metres per second, 5% of the speed of light. Nothing in our everyday experience approaches that, not even the earth’s orbit around the sun comes close to that speed.

How Do We Experience Time Slowing & Length Contracting?

Let's return to Einstein in his tram. As he hurtles down the street, the buildings appear thinner[4]; because length has contracted in his direction of travel. (Since he's not travelling vertically, there's no vertical contraction.) He'd also notice the street's clocks ticking more slowly. Let's look at why this is.

Since there is no universal reference point for space or time we observe the world from our own bubble of reality. Within our own bubble objects move at low speeds relative to each other, and classical physics works fine. But at high relative speeds things are different.

The observer, in his Black bubble of reality, at right, sees a rocket (and its White reality bubble) pass through his bubble at high speed relative to him. The observer sees rocket time passing more slowly than his, be that ticking clocks or human ageing. He also sees that distance measurements (tip to tail) are shorter, while heights remain normal.

But the Principle of Relativity implies the opposite is also true, as at left. So the rocket observer regards his White reality bubble as stationary and the Black bubble, i.e. the rest of space, as moving past the rocket. This means that as relative speed approaches light-speed, those on the rocket observe that space as a whole is shrinking more and more (in the direction of travel).

[4] This characterisation of what an observer (in this case Einstein) sees is helpful when learning about Relativity, but it isn't fully accurate. Due to finite light-speed and the observer's vast speed the image would be distorted in other ways too.

It should be pointed out that ‘bubbles of reality’ are not in fact bubbles or any sort. They are just individual ‘frames of reference’, to use the term introduced earlier. Each individual frame of reference is a personal coordinate system extending to the edge of the universe.

An unsurprising question to ask at this point is, ‘Is this real or just some sort of illusion?’ After all, if both observers observe slowing time and contracting length in the other’s bubble of reality, surely they can’t both be seeing this *in reality*.

However, the effects of slowing time and length contraction have been demonstrated with real measurements as well as in theory. And secondly, it only appears to be a problem because millennia of human experience have conditioned us to think it not possible.

However, a more challenging version of this question is the ‘Twins Paradox’, below, which as we’ll see, is not actually a paradox.

Paradoxical twins

The ‘Twins Paradox’ involves one of a pair of twins leaving the other on earth, travelling a vast distance at enormous speed, then turning around and returning to his or her twin. If relative speed is all that matters, surely each twin observes time slowing for the other twin, and that the other twin has aged less than they have. Since this is impossible, Relativity must be wrong – so the paradox suggests.

This *apparent* paradox relies on the mistaken impression that the relative motion of the twins is symmetrical. However, while the stay-at-home twin’s course through space-time has remained unchanged, the travelling twin has turned around to make her return journey to earth. And that change in direction amounts to a detectable change in direction.

In fact, the travelling twin ages less than the other twin. (To understand why, see the graphical explanation in *A Little Bit of Maths*.) As an example, after 1 year in orbit, space station astronauts return 1/100 of a second younger than if they had stayed on earth.

NB Other apparent paradoxes address length contraction. In one, a ladder travelling at enormous speed and experiencing length contraction is assumed to be able to fit lengthways into a ‘stationary’ barn whose length is shorter than the ladder’s ‘stationary’ length.)

Approaching Light-Speed

Imagine two rockets 'A' and 'B' moving towards each other. They each travel at 60% of light-speed relative to our 'stationary' bubble of reality 'S'. What do they see?

Normal physics says that their combined approach speed is 60% plus 60%, i.e. 120% of light-speed. But Relativity limits relative speed to the speed of light. What happens is that as the rockets' speed increases slowing time reduces the actual relative speed increase, as this table shows.

Speed A relative to S	Speed B relative to S	Speed A relative to B
60% of light-speed	60% of light-speed	88% of light-speed
75% of light-speed	75% of light-speed	96% of light-speed
90% of light-speed	90% of light-speed	99% of light-speed

In Summary

We've discovered that as an observer's bubble of reality travels faster relative to other objects, he observes length contraction and slowing time outside his bubble.

And we've seen that this effect is unnoticeable at everyday speeds. But at speeds approaching the speed of light, 'c', these effects are large; until, at 'c', the universe's speed limit, length has contracted to nothing and time slowed to a standstill. That means that a light beam, travelling at 'c', perceives that is has crossed the whole universe in literally no time at all, as if it had infinite speed. And that's why, on page 35, we said that light-speed is referred to as the universe's 'infinite speed'.

Congratulations, You've Just Done The Hardest Part

The last few pages are the hardest part of Relativity to grasp because they defy our expectations based on everyday experience. But, not only does Einstein's Relativity hold up as a theory, it has been proven in practice in many ways, as we shall see later.

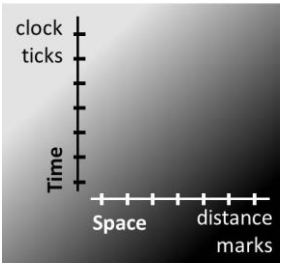
Things are easier to understand from here on, and continue to use simple logic to reach more universe-shattering conclusions.

4 A RADICALLY NEW VIEW OF THE UNIVERSE

INTRODUCING SPACE-TIME

We've seen that the faster an object travels the more its length contracts and its time slows as perceived by a 'stationary' observer. They do so in proportion to each other because of the basic equation for speed and the invariance of the speed of light. Not only that but neither space nor time have absolute reference points.

It seems that space and time are more similar than we perceive based on our low-speed intuition. And so perhaps, rather than being separate entities, they can be regarded as parts of a single four-dimensional (4D) fabric. This so-called 'space-time' comprises three dimensions of space[5] and one of time. The space and time we perceive are but different perspectives of space-time. (In a similar way, a cylinder looks like a circle when viewed from above and a rectangle when viewed from the side.)



The idea of space-time is called into existence by Relativity. It has not been directly observed, but that doesn't really matter. The fact is that this model explains observations and makes correct predictions about the motion of objects. If you prefer to conceive the intimate relationship between space and time differently, by all means do. Just be sure that your model of the universe allows the invariance of the speed of light and the Principle of Relativity to coexist. That is what lay behind the problematic tension which led Einstein to Relativity in the first place (see page 35).

But perhaps space-time is not such a surprising idea. We're used to hearing that distant galaxies are a large number of light-years from us. A **light-year** is the distance light travels in a year. Our sun is 8.5 light-*minutes* away. That's *only* 150 million kilometres! So if we ask, 'how does the universe look now?' we can't possibly know. We

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[5] The three dimensions of space are: up/down; side to side; forwards/backwards.

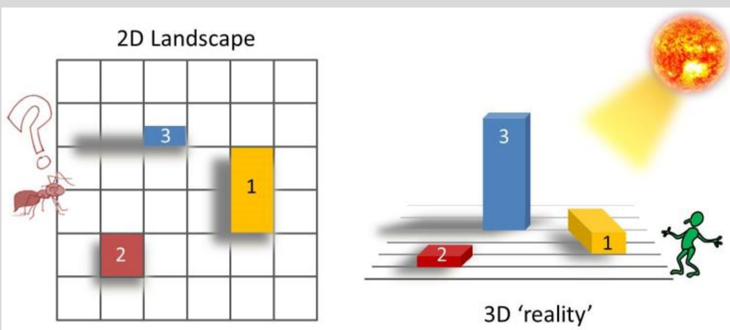
can only know how the sun looked 8.5 minutes ago, or how the edge of the visible universe looked 13.8 billion years ago. So it seems that space and time are already bound together in any attempt to describe the universe.

VISUALISING SPACE-TIME

It's difficult to imagine what 4D space-time looks like. To start, let go of the idea that the four dimensions *describe* the universe. Instead, consider space-time as a 4D fluid which *is* the fabric of the universe.

Challenging preconceptions: the limits of our 3D senses

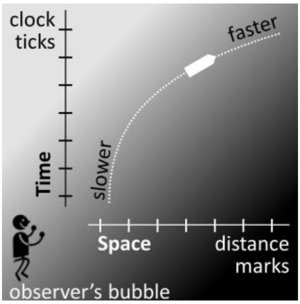
Human survival has not required humans to visualise 4D so we've not evolved that ability. Since we can't visualise 4D space-time, it's helpful to understand the limits of our 3D intuition by analogy to a 2D being.



A 2D ant, asked to order the block in their landscape by size (at left in the graphic above) will say: 1, 2, 3. The ant, with no conception of 'up', or physical ability to look 'up', cannot see that the objects have height, as at right in the graphic. We, 'superior' humans, able to see the third dimension of space, arrive at a different order: 3, 1, 2.

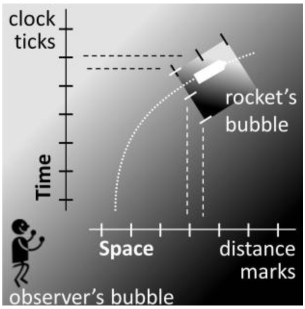
Furthermore, our 2D ants, with no conception of 'up', have long been bemused by the dark grey patches that appear to move around each object. Then one day a 2D Einstein says, 'What if these objects have a third dimension, let's call it *height*? And what if the day and night we experience is because of a bright light that moves in this third dimension? Maybe the height of the objects would block out the light and create dark grey *shadows* that move as the bright light moves.'

VISUALISATION OF CONTRACTING LENGTH AND SLOWING TIME



Let's see what happens when a rocket moves relative to a 'stationary' observer, as at left. The faster it travels, the more its trajectory tilts toward the horizontal. That's just normal physics: it covers more distance (horizontally) in a given time (vertically).

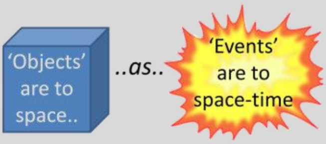
However, Relativity reveals that it's actually moving through 4D space-time and not just through space. Therefore, the rocket's bubble of reality, its '**frame of reference**', also tilts toward the horizontal compared to the observer's reference frame, as at right.[6]



If the observer could physically see the rocket's reference frame she'd notice that the gap between its distance markers looks short compared to hers, likewise its time markers. The ruler analogy on page 19 helps understand why. (NB. It isn't due to the distance between observer and rocket. They could be close to each other but its reference frame will still have tilted.) As a result the observer concludes that the rocket and any ruler on board have shrunk and rocket-time has slowed. Those in the rocket don't observe change in their reference frame: to them, their rulers and clocks measure as before. In fact, since motion is relative, they believe the observer's frame has tilted, and hence that the observer's space has contracted and their time has slowed.

Events

In 3D space we talk about objects in terms of 'what' and 'where'. In 4D space-time, we talk about 'events', a more complete description: 'what', 'where' and 'when'.



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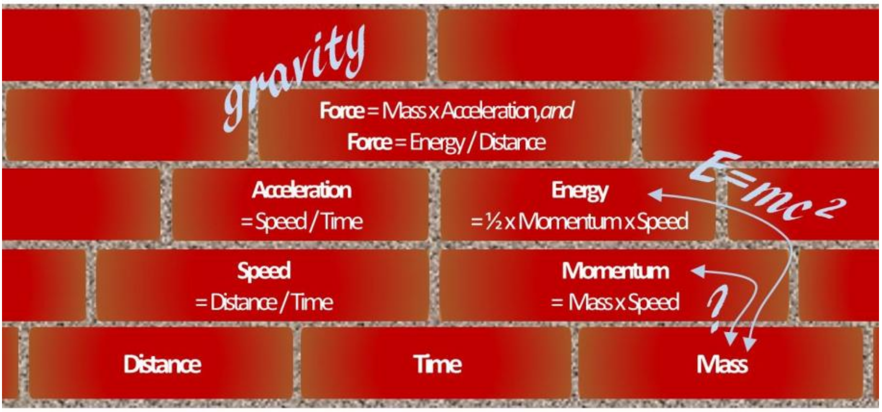
[6] (a) This is a conceptual model, not a depiction of reality. (b) It's a simplified form of a tool used by physicists: 'Space-time diagrams' - see *A Little Bit of Maths*.

5 REVISING THE LAWS OF PHYSICS

MAINTAINING THE BRICKWORK

Up until Einstein, the laws of physics governing how objects move and interact seemed set in concrete. These laws related to things like acceleration, momentum and force, including the force of gravity. They were derived from the fundamental properties of distance and time. The laws worked just fine in a low-speed universe.



The equations describing the laws of physics are derived from the basic properties of distance and time. If, as Relativity shows, these fundamental properties vary with speed, then all the equations upon which they depend will be affected in some way.

However, Relativity demonstrated that these fundamental properties are not rigid but vary with speed; especially at vast light-like speeds. Einstein's Relativity appeared to be shaking the very foundation stones upon which the rest of physics had been built. So the equations describing the laws of physics needed modifying to ensure that they worked at all speeds. This led to more expectation-shattering insights and heralded the dawn of the nuclear age.

We will look: first at momentum (and the confusion about *apparently* increasing mass); then the relationship between 'mass' and 'energy'; and then at 'force', and specifically what Relativity has to say about how the force of gravity actually works.

SOMETHING ODD *APPARENTLY* HAPPENS TO 'MASS'

A fast-moving car causes as much damage to a brick wall as a slow-moving lorry, implying that both speed and mass contribute to their 'motion-energy', known as **momentum**. If we give the car more energy, it goes faster and gains momentum.

The final column in the table on page 43 shows that the gain in relative speed between A and B reduces despite the extra energy spent accelerating the rockets from 60% of light-speed to 75% and then 90% (as shown in the first two columns.) Some energy seems to have gone astray. But that would be against the law of **conservation of energy and momentum**. It states that the total amount of energy and momentum must stay the same; it can't be created or destroyed. What Relativity reveals is that this 'missing' energy is actually increasing the rockets' momentum, which approaches infinity as the rockets approach light-speed. Since that would require an, impossible, infinite energy input it implies that objects with mass can't actually travel that fast.

In order to help explain this to laymen who might not understand the term 'momentum', physicists used to talk about an increase in mass; even though there was no suggestion the rockets were suddenly made of more matter! What they were actually trying to say is that it would become harder and harder to accelerate the rockets, *as if* they had increased in mass.

MASS-ENERGY EQUIVALENCE, AND THE FAMOUS EQUATION $E=mc^2$

Mass and energy, more similar than we tend to think

We saw in the table on page 43 that as we repeatedly provide more energy to an object it gains ever greater momentum, and ever smaller amounts of speed. The clear implication is that the extra energy is being converted into the *equivalent* of mass rather than speed.

The reverse conversion was already well-known by the time Einstein came along: as radioactive materials such as uranium decay they not only radiate energy (as radioactivity, including electromagnetic waves), but they also lose mass.

These conversions between mass and energy led Einstein to the insight that there must be some equivalence between the two.

Light, a wave or a particle?

To the question, 'light – particle or wave?' the surprising answer is both. So far we've been describing light as a wave. We're used to thinking of light of different colours, as in a rainbow. Each colour is actually light of a different wavelength. But many people also talk about 'photons' of light, probably conjuring an image of particles. (Newton had argued that light comprised of tiny 'corpuscles'.)

Despite Maxwell's Electromagnetic Wave Theory, light's other behaviours, such as photo-electricity, suggested light was formed of packets of energy, called **photons**[7], rather than being spread out in a wave. It was Einstein who developed the idea of photons and their particle-like nature in his first ground-breaking paper of 1905.[8]

This dual behaviour, known as '**wave-particle duality**', is explored further in the chapter *Theory of Everything, Quantum Matters.*

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[7] The term 'photon' for this packet of light energy came into use from 1926.

[8] Einstein published four important papers in 1905, his so-called '**Annus Mirabilis**', two of them on Relativity. A third paper on photo-electricity was called, 'On a Heuristic Viewpoint Concerning the Production and Transformation of Light' and earned him a Nobel Prize. (See quote on page 74.)

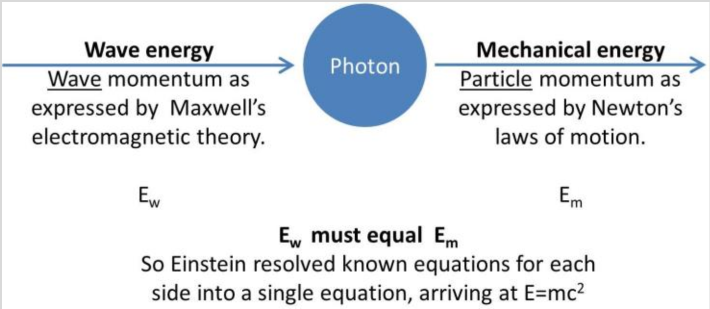
Arriving at $E=mc^2$

The equation $E=mc^2$ joins together the otherwise completely separate concepts of energy 'E', and mass 'm', through the speed of light 'c'.

Thought Experiment #4: Light as a cannonball

Einstein realised that if a light beam hit an object it would transfer its 'momentum' and hence its wave energy to those objects, just like a cannonball does. The mechanical energy gained by the object is explained by Newton's laws and can be calculated. Einstein also knew from Maxwell's Electromagnetic Wave Theory how to calculate the momentum energy of light.*

His light-as-a-cannonball thought experiment allowed him to equate wave energy and mechanical energy, and by combining Maxwell's and Newton's equations, Einstein arrived at his famous equation, $E=mc^2$.



It is not intuitive that we arrive at such a simple equation. That's just the way the maths falls out.[+] (See *A Little Bit of Maths* to see how.) But we can see how Einstein's breakthrough thinking led him there.

* It was well known, from Maxwell's Electromagnetic Wave Theory, that light had momentum despite having zero mass.

[+] The equation $E=mc^2$ was initially written differently by Einstein.

Matter is 'just' high density energy

$E=mc^2$ underlines the fact that matter and energy are more closely related than we imagine; more like the relationship between space and time we saw earlier. In this equation 'c' is the speed of light, nature's constant: the speed constraint which applies to space-time.

The equation gave rise to a startling idea: if ‘E’ and ‘m’ are very simply related by ‘c^2’ then maybe matter was ‘just’ made of energy, albeit so densely packed that it took on the properties of matter. Indeed, physicists refer to this as ‘**mass-energy equivalence**’, and will often use the term ‘**energy-density**’ whether referring to less dense ‘energy’ or more dense ‘matter’.

It is awe-inspiring to find ‘c’ popping up here in this role. Once again, we are peering into nature’s very design of the universe.

Nuclear reactions, converting matter to energy

And, if matter is ‘just’ highly dense energy, then the simplicity of the equation $E=mc^2$ also implies that matter can be *completely* converted into energy and vice versa. And not just *partially* through chemical reactions such as burning.

Since ‘c’ is a huge number (300,000,000 m/s), so ‘c^2’ is enormous (nearly 100,000,000,000,000,000), and Einstein’s equation highlights the vast amount of energy locked up in matter.

It is from this that the threat and opportunity of nuclear reactions derives, whether in nuclear fuel or nuclear bombs. The ‘**nuclear forces**’ that keep the sub-atomic particles (protons, neutrons and electrons) bound together into atoms are exceptionally powerful. Nuclear reactions break apart or modify these bonds, releasing some of that power in the process.

Nature had, of course, invented nuclear reactions long before Man. For example, in radioactive materials, and as the underlying process that fuels stars, including our own sun.

It’s worth mentioning that gravity is insignificant by comparison. Nuclear forces are up to 10^{40} times stronger than gravity (that’s 10 followed by 40 zeros). If this seems surprising, it’s because we never actually directly experience nuclear forces (they have an exceptionally small range of influence); and because while gravity is a weak force by comparison when applied to massive objects like planets it becomes significant.

An Explanation For Gravity

It's gravity, but not as we know it

Continuing his review of the laws of physics, Einstein turned his attention to gravity. Newton had provided very accurate equations by which to calculate gravitational attraction between two bodies moving at everyday speeds. But he had not explained at all how gravity actually worked: from where that 'force of attraction' came.

Einstein realised, with the help of a further thought experiment, that gravity might not actually be a force of attraction at all.

Thought Experiment #5: 'The happiest moment of my life'

Einstein described as '*the happiest moment of my life*' one particular flash of inspiration. *'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. This led me to the theory of gravity.'*

Einstein had realised that a man falling from a building and a man in a rocket floating freely in space experience weightlessness in exactly the same way. Indeed, if both are blindfolded and wearing a spacesuit, and are suddenly awakened from a sleep, they would have no way of knowing which situation they were in.

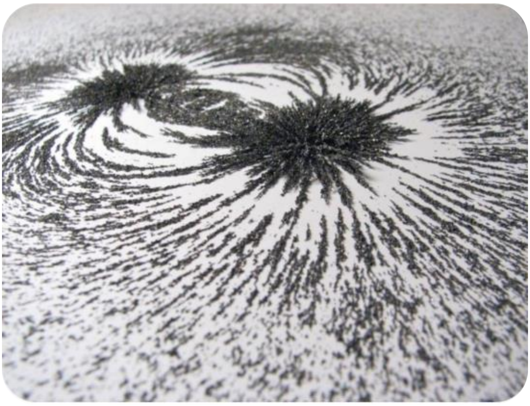
And when the falling man reaches the ground (hopefully on his feet), or the rocket starts to accelerate, the sensation (i.e. pressure between feet and floor) will also be identical for both.

Einstein called this the '**Principle of Equivalence**' between acceleration and gravity.

But, if gravity is 'just' an effect perceived by objects as they accelerate through space-time, what is it that creates that acceleration?

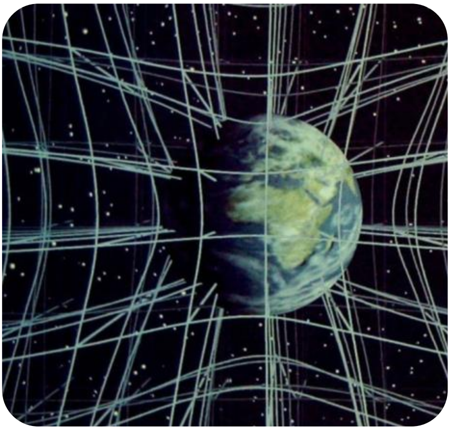
Matter causes space-time to curve …

We've described space-time as the 'fabric' of the universe. That's a little vague. Space-time is a bit like a magnetic field. Indeed, physicists talk about the '**space-time field**'.



School science experiments use iron filings to 'observe' the magnetic field created by a magnet. The graphic at left shows how the magnetic field lines are curved when two magnetic objects are brought into the magnetic field.

We can extend this analogy to an object in space-time. The object's mass interferes with space-time, concentrating the space-time field in the object's vicinity, see graphic at right. And, just as objects can be made to float in sufficiently strong magnetic fields, a mass 'floats' in the space-time field. (This is just as Man has described stars and planets for centuries, as 'floating' in space.)



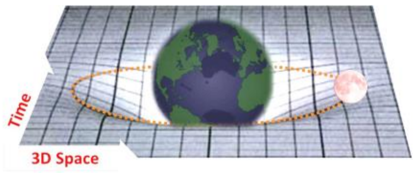
This curvature of space-time effectively creates a pressure on objects which they experience as gravity, as we are about to see.

… and space-time tells matter how to move

We saw earlier that it is impossible for us, as 3D humans, to fully visualise 4D space-time. But there are some visualisations which can help us understand important concepts.

In the visualisation in the graphic below, the 3 dimensions of space are represented by one axis of a 2D grid painted onto a rubber sheet, and the 1 dimension of time on the other.

The effect we saw above of the curving of space-time's 'field lines' by an object with mass can be seen, in this graphic, as a depression in the rubber sheet. The result is that any smaller objects close by are drawn toward the larger object, just as a marble would be drawn to roll down the curves of the rubber sheet. In other words, there is no separate force of gravity; it is 'just' the result of an object responding to the curving of space-time.



> Matter tells space-time how to curve and curved space-time tells matter how to move.
> *John Wheeler*

The smaller object can remain in orbit (rather than roll down the curve altogether) if it is travelling at speed around the larger object; just like whirling a stone on the end of a piece of string. Similar mechanisms keep the moon, planets and stars in their orbits, and lie behind the gravitational influence of galaxies.

The problem with conceptual visualisations of space-time

While visualisations of space-time explain part of a concept they can also create false impressions. For example, the rubber-sheet analogy misleads as follows.

- It is natural for an object to depress a rubber sheet because of gravity pulling from below. But, pausing to reflect, we realise that:
  (1) since the analogy *explains* gravity, there is no gravity acting from below; especially as it is set in deep space and not on earth.
  (2) we don't know *how* matter actually interacts with space-time to create the impression of mass and so cause space-time to curve. (This is something in which the famous '**Higgs Boson**' plays a part.)
- It suggests that space-time is a stable rigid grid-like structure. But as we'll soon see, space-time, i.e. the universe, is actually expanding all the time.

A definition, 'mass' versus 'weight'

No matter how massive, an object floating freely in space has no weight. That's why we say it's 'weightless'. But it is still made up of matter of course, and therefore still has a quantity we call 'mass'.

'**Mass**' is a measure of the amount of matter in the object. On the other hand, '**weight**' describes the force between two objects, and this varies depending on their relative motion and their masses. For example, the feeling we get in a lift of being momentarily heavier as it starts accelerating upwards. Alternatively, the fact that a man weighs six times less on the moon than on earth because the moon is six times less massive.

Four-Dimensional Geometry

We've seen that curved space-time dictates the motion of objects, and when we look at the graphic on the previous page, we can visualise why. But what is actually going on?

The rules of geometry which we learned at school apply to a flat, 2D, piece of paper. In 2D geometry, the shortest distance between two points is a straight line.

In 3D or even 4D curved space, the shortest possible line that can be drawn between two points is a line that follows the contour of the curve. That's why airplanes from London to New York don't fly straight across the Atlantic, but actually route over Greenland.

Returning to our object influenced by curved space-time, it too is just trying to follow the shortest distance between two points, *on the curved surface of space-time*.

Bending Light

We saw earlier that mass and energy are equivalent, and we went on to say that physicists often use the term 'energy-density' whether referring to less dense 'energy' or more dense 'matter'.

Light is a form of energy, for example giving life to plants and animals or causing burns. It therefore has an energy-density despite not having any mass. For this reason, the path of a beam of light passing through curved space-time will be deflected.

BLACK HOLES AND SINGULARITIES

If the object causing the curvature of space-time is sufficiently massive, space-time curves away into a so-called '**black hole'**. The energy-density at the very centre of the black hole is so great that it creates an infinite curvature of space-time, like a bottomless well in the space-time fabric. This is called a '**singularity'**, and any matter or energy (such as light), once drawn in, cannot escape.

GRAVITATIONAL REDSHIFT, GRAVITATIONAL TIME DILATION

Imagine light trying to leave a massive star. Two things will happen to the light beam.

As we've just learned, light is influenced by gravity. The star's gravitational influence will try to pull the light beam back, causing the light's wave to be stretched. To an observer, this longer wavelength light will shift the light's colour toward the red end of the spectrum. This is called '**gravitational redshift**'.

In terms of space-time geometry, the light beam is travelling a longer curved path out of the curved space-time in which the star sits. But Relativity also tells us that the observed speed of light is the same for all observers. So time, for an observer near the massive star, must be slower if he is to arrive at 'c' in his calculation of the light beam's speed. This phenomenon is called '**gravitational time dilation**' to differentiate from the time dilation caused by relative speed difference. In other words, time is slowed whenever there is a difference in gravity between two points. For example, a clock on earth will tick more slowly than a clock in orbit around the earth.

In a black hole from which light cannot even escape, the time dilation is such that time actually slows to a complete standstill.

NOTHING EXCEPT EMPTY CURVED SPACE

Relativity reveals two previously unknown deep relationships: the one between mass and energy, and the one between space and time. We have also seen that these two relationships are themselves connected: '*Matter tells space-time how to curve and curved space-time tells matter how to move*'.

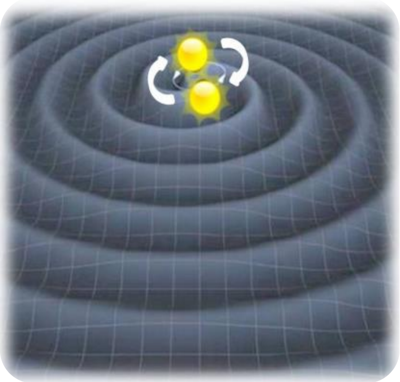
John Wheeler, who gave us this last quote, also put the implications of Relativity into a nutshell.

'There is nothing in the world except empty curved space. Matter, charge, electromagnetism, and other fields [such as gravity] are only manifestations of the curvature of space.'

GRAVITATIONAL WAVES

Among the many predictions made by Einstein arising from Relativity was the existence of '**gravitational waves**'.

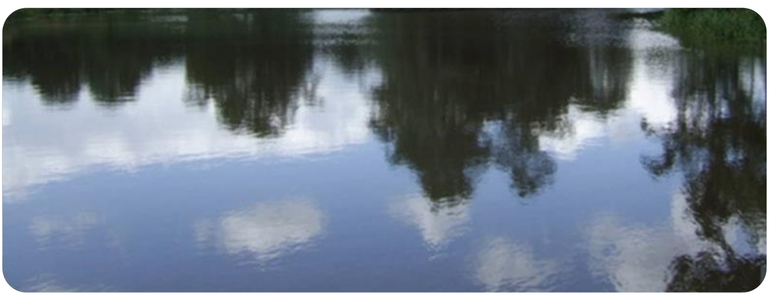
To understand these, imagine a perfectly frictionless sphere spinning 'on the spot' in water. Because the sphere is frictionless, the water remains undisturbed. But, if the rotation is unbalanced in some way, or the sphere suddenly removed altogether, the water will be disturbed and, as a result, water waves will ripple outwards.



Similar 'gravitational waves' are expected to be found in space-time emanating, for example, from 'binary stars', see right. (Binary stars are two massive stars orbiting each other extremely fast, measured in minutes rather than days or years). With such rapid orbiting, the binary pair would continuously whip up and disturb space-time's fabric creating gravitational waves, often described as 'ripples in space-time'. And of course, since nothing can travel faster than 'c', the gravitational waves are also limited by this universal speed limit.

Experimental evidence for gravitational waves was announced on February 11th 2016, becoming the last of Einstein's predictions to be confirmed. But what do gravitational waves mean in practice?

If everything in the universe, everything we see and experience, are, as John Wheeler put it, 'manifestations of the curvature of space', we might picture galaxies, stars, planets and indeed ourselves as somehow woven from the fabric of space-time. And when something disturbs the fabric, waves in space and time ripple outwards. Indeed, just by walking down the road, we all create exceptionally tiny gravitational waves. These waves cause objects they pass through to bend and stretch in response, rippling these objects in the same way as a reflection being rippled on the surface of a lake.



However, these ripples in space-time are so weak in our calm backwater of the universe called earth, that they're barely detectable.

What happens if the sun suddenly disappears?
Imagine our sun suddenly vanished from the solar system. This would constitute quite a disturbance of space-time. It would take 8½ minutes for us to notice the light disappear from the sky; that's the time it takes for light to travel to earth. But, it would also take 8½ minutes for the Earth to register the absence of the sun's gravity and fly off, out of its orbit, deeper into space. That's how long it would take the gravitational wave disturbance carrying the information about the Sun having vanished to travel to us.

6 INSIGHTS INTO THE UNIVERSE'S DESIGN

COLLAPSING UNIVERSE … OR … EXPANDING UNIVERSE?

There is nothing much within Einstein's model of the universe that prevents gravity from causing the whole universe to collapse in upon itself. The mutual gravitational attraction of the universe's matter should cause it to collapse like a deflating balloon.[9]

There is only one workable reason it wouldn't do so, and that's if it was forever expanding. Even if at some point the universe had achieved some sort of stability, it would take only a small disturbance (for instance a collision) to introduce instability leading to collapse or expansion; much like a pencil, finely-balanced on its end, topples if nudged even slightly.

But, in the early 1900s, astronomers looking into the night sky with instruments then at their disposal, observed a universe that looked static and not one that was collapsing or expanding. So Einstein adjusted his equations to counter-balance this theoretical tendency to total collapse, enabling his equations to describe a static universe. However, by 1929, conclusive evidence for an expanding universe had been found. So Einstein did away with his adjustment, and the search began for the mechanisms driving the universe's expansion.[10]

As the universe expands, its galaxies are being carried ever outward by the tide of expanding space-time. (More accurately, it is the three dimensions of space which are expanding while also progressing forwards in the time dimension.)

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[9] Indeed, this would also be true of Newton's 3-dimensional universe, except that he assumed the universe was infinite, thereby avoiding its theoretical collapse.

[10] Einstein called this adjustment the '**cosmological constant**'. Despite its removal from his equations by Einstein at the time, a version of this has reappeared in recent decades. This has arisen as cosmologists try to explain how our universe can be ever-expanding by incorporating new ideas about 'dark energy'.

A Big Bang

If the universe is expanding, it suggests there was a beginning to the expansion. And since by 'universe' we mean space-time then, at that beginning, space is shrunk to nothing, and time does not exist. (If this sounds similar to the black hole singularities we met earlier, you're right, it is.) From here, some theories suggest, the universe came into existence through an explosive '**Big Bang**'. (Alternative theories suggest that the Big Bang could be more of a 'bounce' back from a previous collapsing universe.)

Light-speed Is Very Special

Why can't anything travel faster than light?

Because at that speed space has shrunk to nothing and time has slowed to a standstill, as far as the object doing the travelling is concerned. Furthermore, as we've also seen, it would take infinite energy to accelerate an object with mass to that speed.

So, it's not because there is anything special about light that it can travel that fast; it's just because it has no mass and so can travel at the fastest speed the universe allows. Other massless particles (or waves) can reach this speed too.

While Einstein's equations indicate it's impossible to travel faster than light in a vacuum, we should bear in mind that scientists used to argue that man-made objects could not travel faster than sound. Some scientists are today considering how faster-than-light travel might become a reality. As ever, it's best to never say 'never'.

Designing the universe

What we've discovered is that the universe is defined by fixed parameters, but these are not the properties of distance and time. It is instead defined by constants such as the speed of light - one of nature's design parameters. Not only is it the universe's speed limit, but it also defines the relationship between space and time, and between mass and energy.

WHAT IS SPACE-TIME MADE OF?

Relativity calls into existence 'space-time' with some certainty. So presumably there's a pretty clear idea what it's made of. Unfortunately not.

In this book, we've used words like 'fabric', 'fluid' or 'field' to describe space-time. And we've used concepts like '4D', 'lattice' or 'rubber sheet' to help visualise space-time's curvature. But, to be fair, we've also said that 'no-one has actually seen space-time', and that reflects the current state of physics. All we know is that this model works at explaining how various aspects of the universe work.

There is much debate among physicists about what space-time might be made of. A few theories are being worked on, and current or planned experiments aim to delve ever-deeper into the make-up of matter and energy. The competing ideas all suggest that at the very smallest scale space-time itself comprises some form of fluctuating field of energy. (See also page 82.)

Whichever the right theory it will need to answer how space-time, whatever it is made of, assembles itself to produce the universe which Relativity has revealed. And then physicists will have another question to answer: what gave rise to whatever that 'stuff' is?

So, while the universe is clearly not as it seems - it seems we must continue waiting to find out what the universe actually is.

> It was formerly believed that if all material things disappeared out of the universe, time and space would be left. According to the relativity theory, however, time and space disappear together with the things.
>
> *Albert Einstein, when asked for a short explanation of Relativity, prefacing it with, 'If you will not take this answer too seriously.'*

7 A FEW LOOSE ENDS

WHAT DOES 'RELATIVITY' ACTUALLY MEAN?

The word 'Relativity' refers to the Principle of Relativity. As we have seen this states that we can only describe the position or motion of one object *relative* to other objects.

'Special' and 'General' Relativity

Einstein's 1905 paper on '**Special Relativity**' applied to objects moving relative to each other with unchanging speed and direction. It was 'Special', because it applied only to this 'special' case.

Understanding the relativistic effect on objects which were changing speed or direction took Einstein a further ten years. He first presented this work in 1915 and published his paper on '**General Relativity**' in 1916. This was 'General' because it applied to any objects, however they are moving.

What's in a name?

Einstein regretted the name 'Relativity' because of inappropriate popular use.

It led some to understand that everything was relative and varied with speed, even the laws of physics. But, as we've seen, the laws of physics are *absolute* and always operate in exactly the same way. It is only the properties upon which the laws operate which vary with speed: distance and time.

But Einstein's regret at the name 'Relativity' went beyond misunderstood science. Relativity was taken up by proponents of 'Relativism' to support their belief that there is no absolute truth or validity for anything, for instance as applied to morals. While arguments can be made for Relativism, Relativity is at best a very poor example since, in actual fact, it presumes that the laws of physics are absolute.

If All This Is True, Why Don't We See Any Of It?

Let's go back to the earlier analogy on page 13 where we grew up on a gently rolling plain, as far as the eye could see, with no knowledge of huge mountains or vast oceans. In a similar way, our planet Earth is in one of the many calm backwaters in an elsewhere tempestuous universe. In these calm backwaters there are no truly massive objects, nor large objects travelling at vast light-like speeds relative to each other.

We should be grateful. Being caught up in such tightly curved regions of space-time, for instance around black holes, would be far worse than being caught in the middle of a raging sea. Life as we know it could not exist in such regions. Enormously powerful 'waves' of length contraction and slowing time would tear us apart, not just limb from limb, but atom from atom.

It is only with the development of far more sensitive instruments and telescopes that our technology-assisted human senses are increasingly able to detect the effects of Relativity.

How Wrong Was Newton?

It might seem that Newton, or at least his theory, comes out of this story somewhat tarnished. That would be an incorrect perception. He is rightly hailed as one of the scientific greats because of his achievements. His theory, understandably, could not account for phenomena which in his day had not even been observed.

> Let no one suppose, however, that the mighty work of Newton can really be superseded by [Relativity] or any other theory. His great and lucid ideas will retain their unique significance for all time as the foundation of our whole modern conceptual structure in the sphere of natural philosophy.
>
> *Albert Einstein*

And, even more than that, we can say that Newton was right: for a *mass-based* view of the universe. Newton's Laws are still used today, serving perfectly well for most everyday low-speed purposes.

Einstein's Relativity describes a richer, more inclusive, *energy-based* view of the universe. One underpinned by the invariance of the speed of light and the Principle of Relativity, and which encompasses, and extends beyond, Newton's mass-based laws.

What Michelson-Morley's 'failure' tells us about scientific research

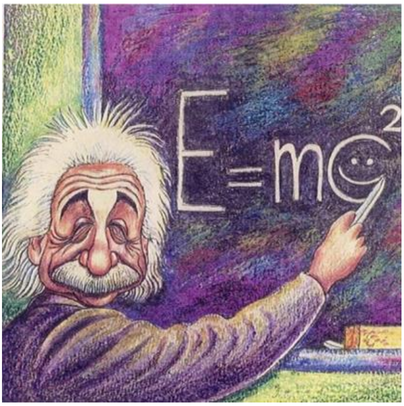
It seems ironic that the Theory of Relativity followed Michelson-Morley's 'failed' attempt to find evidence for the ether, the presumed medium for transmitting light. The irony is that it contributed, after all, to such important advances in our understanding of the universe.

Michelson and Morley were highly respected scientists. The fact that they did not achieve their aim was no doubt a huge disappointment which may have caused them to consider going back to the drawing board. They were not to know in 1887 that their 'failure' would help unlock a new understanding of the universe, contributing to the development of important theories as well as practical systems upon which we rely every day.

It's a demonstration of the importance of basic scientific research, and that we can learn from our 'failures' as well as from our successes.

YOU MADE IT!

Congratulations, you have come to the end of the tricky explanations of Relativity.



You should feel good about that even if you feel your grasp is in some way incomplete. You would not be alone in taking time to absorb the broad and conceptually challenging topic of Relativity.

Let's remind ourselves quite how broad and challenging it is.

A Summary Of Relativity's Startling Conclusions

- The underlying fabric of the universe is four-dimensional space-time. Space and time are not rigid or absolute properties. There are no universe-wide reference points from which everything is measured.
- Our sense that the universe is defined by the properties of distance and time is wrong. It is defined by rigid parameters, nature's constants, such as the speed of light.
- The speed of light is the universe's speed limit for objects and for information about events. As moving objects approach this speed, relative to observers, it appears to the observers that the object's length has shortened, its time-keeping clock has slowed and it behaves *as if* its mass has increased.
- The separateness of space and time which we experience arises from our limited perceptions (narrow glimpses) of space-time. Space and time are actually more similar than we perceive.
- The universe, i.e. space-time, is expanding, carrying all energy and matter with it as it does.
- Energy and matter are equivalent, related one to the other by the speed of light. Matter is just very high density energy.
- The presence of matter or energy causes space-time to curve. This curvature in turn results in the force which we experience as gravity.

In short, the relationship between space**,** time**,** energy**,** mass and the speed of light is inextricable. It is cemented into the fabric of the universe. It is how the universe is built.

Chapter

NEXT TIME YOU GAZE AT A CLEAR NIGHT SKY

Next time you gaze up at a clear night sky, stop. Look deep into the Infinite and picture Einstein's Universe; a gently bubbling ocean of Energy, pure Darkness.

Here and there more densely-packed in vast clouds of gas or even denser galaxies; at times so compressed as to fuel suns and form planets which bring forth Light and Life. And again denser still, such that not even fleeting Light can escape the Blackness.

Peer deeper still. Now imagine an ocean of Energy woven from the all-enveloping fine silk of Space and Time; itself curved to greater or lesser degree according to the influence of material nearby; Gravity's baton, in this way, gently conducting the graceful Motion of the Heavens.

And know, in that moment, that 'c' the universe's Infinite Speed runs its mathematical rule on all this majesty.

Chapter

WHERE'S THE PROOF?

This chapter describes the significant physical evidence for Relativity, and also discusses what 'scientific truth' really means.

RELATIVITY PROVEN …

The test of a good theory is in three parts. Does it: explain what we know, make valid predictions, and help us build things that work? Here's a summary of Relativity's proofs.

- Relativity **explains Michelson-Morley's finding** that the speed of light is independent of an observer's relative motion.
- Relativity explains why the **observed orbit of Mercury** is subtly different to that calculated by Newton's Laws. The finite speed of gravitational influence means that at any moment in time, the planet is attracted to where the sun was a moment before. This causes the orientation of its elliptical orbit to constantly shift and is called 'precession'. It affects all planets, but Mercury's small size and proximity to the sun means that the, albeit tiny, shift is measurable.
- The **bending of starlight** by massive objects was a predictable result of Newton's Laws. However, only Relativity precisely predicts the extent of bending, as demonstrated in 1919. (The degree of precision of the 1919 results has been questioned, but the experiment has in any case been repeated and confirmed.) **Gravitational lensing**, commonly used by astrophysicists, uses the bending of starlight to magnify distant objects.
- Relativity's equations support the observation first made in 1929 that the **universe is expanding**.
- **Gravitational redshift** of the light from a massive burned out star, known as a white dwarf, was verified in 1959.
- The first **black hole** was discovered in 1971.

- The **experimental proof of time dilation** (i.e. of time slowing). In 1971, two highly accurate atomic clocks (able to measure time to a ten-billionth of a second) were synchronised and flown in opposite directions around the world. Upon their return they were compared with a stay-at-home clock and found to have drifted apart by a tiny amount, matching Relativity's predictions.
- Relativity explains the **unexpected behaviour of muons**. These particles, created by cosmic rays colliding with the earth's upper atmosphere, should decay before reaching the earth's surface. But muons travel at near light-speed, so they observe significant length contraction in the distance to the earth's surface, most reaching ground detectors more quickly, before decaying.
- The **experimental proof that gravitational waves exist** was made in 2016. (Einstein had himself believed that these might be too weak here on earth to be measureable.)
- The opportunity and threat arising from mass-energy equivalence and observed in **nuclear reactions**.
- The design of **body scanners and particle accelerators** which require precise control of the path of particles moving at speeds in excess of 99% of the speed of light. Engineers must account for relativistic effects to build working systems.
- The design of **satellite navigation systems**. When first launched, they had a 'switch' in their programmes that could turn relativistic corrections on or off. When turned off discrepancies, due to gravitational time dilation, appeared in map positions.

… BUT NOT FOR SOME PEOPLE

The Theory of Relativity was controversial for many years. The science was complex and its conclusions and implications contrary to most people's beliefs. Much pseudo-science arose seeking to refute it; a minority motivated by religious conviction and some, primarily in inter-war Germany, by anti-Semitism toward Einstein (see *Relativity, Culture and Society*).

Einstein himself despaired. '*This world is a strange madhouse. Every coachman and every waiter is debating whether relativity theory is correct. Belief in this matter depends on political affiliation.*'

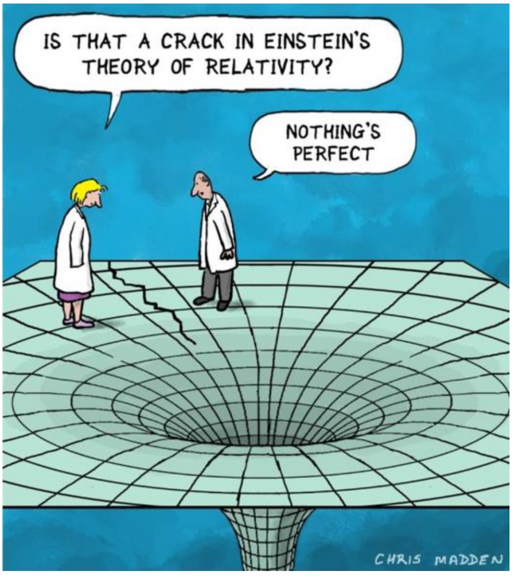
In the early 1900s, Relativity was too controversial to award Einstein a Nobel Prize for this work. So instead the Nobel Committee, impatient to recognize Einstein, awarded him the 1921 Nobel Prize for Physics for his other ground-breaking work of 1905 on photo-electricity.

Relativity continued to be hotly debated in scientific circles well into the 1920s. Some serious and well-intentioned scientists questioned Relativity Theory's assault, as they saw it, on the very foundations of physics.

Today, Relativity is far less controversial but remains little understood outside parts of the scientific community. Nonetheless, engineers and scientists go about their business relying on Relativity's equations, and we in turn rely on the systems they build. Despite this, there is still a tiny but active minority of doubters, who lie outside the mainstream of scientific opinion.

… And Not Forever

Just as Newton's theory eventually failed to explain everything, so too will the time come for Relativity to be amended. And, just as Relativity encompassed Newton's Laws, it is likely that any new theory will encompass (or amend) rather than replace Relativity.



Ironically, it may turn out that Einstein himself set in motion the finding of evidence which Relativity fails to explain. In predicting the existence of gravitational waves he set physicists the challenge of building instruments to detect them. Now these instruments, gravitational wave telescopes, exist and we can probe into the universe’s furthest reaches and deeper into its history. Just possibly it will be here in these echoes of the universe’s earliest moments, or in its most massive and turbulent objects, here where our known laws of physics are most tested, that Relativity will be found wanting.

Is Relativity True?

Science is not a search for ‘truth’, but for models which explain what we observe. The more we learn, the more the models evolve.

Most people who believe in Newton’s theory do not understand the mathematics of calculus he invented to explain how planets move. But they believe in some working model of gravity and orbits because (they have been told) it works. So why should we doubt Relativity, just because it astonishes or because we don’t understand the maths? It would be like saying to a heart surgeon that before he or she can replace my diseased heart, I need to understand the biochemistry, physiology and operating procedures upon which he or she relies.

So is Relativity a question of faith? After all, you might say you need faith in your heart surgeon. But this is a different faith from religious faith. The one founded on personal conviction, the other on reproducible evidence and independent validation.

The Greeks started the serious search for explanations of how the world works, mostly conducted as philosophical inquiry, i.e. thinking about things. 3,000 years later, evidence and the rigour of the scientific method came to the fore.

	Religious Belief	**Philosophical Inquiry**	**Scientific Method**
is a search for …	Truth	Meaning	Working models
described by …	Stories & doctrines	Ideas & arguments	Theories & proofs
& founded on …	Faith & personal revelation	Logic & independent agreement	Reproducible evidence & independent validation

It's interesting to note that Einstein's many insights were the result of 'thought experiments', a sort of philosophical inquiry, and for which scientific methods then found the supporting evidence. It is an approach which scientists probing the cosmic and quantum worlds continue to use.

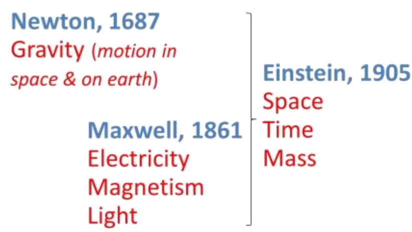
Chapter

THEORY OF EVERYTHING, QUANTUM MATTERS

To fully appreciate Relativity, it is helpful to see it in the wider context of modern physics. This chapter discusses how Relativity forms a part of physicists' on-going search to explain how the universe works at the smallest scale as well as the large scale. Their aim is to find a single unifying 'Theory of Everything'.

QUANTUM WORLD, ORGANISING ENERGY

We've seen how Einstein's Relativity encompassed the work of Newton and Maxwell, and redefined our sense of space and time for large scale objects.



But physicists also wanted to understand what stuff is made of, at the microscopic scale of atoms and even tinier particles.

Relativity had touched on this. Matter comprises very dense energy. That's what $E=mc^2$ tells us. But it didn't explain how energy is organised such that the material world appears the way it does. The physics of the small scale is known as '**Quantum Mechanics**'. The word '**quantum**' has the same root as the word 'quantity' and means 'a fixed amount of energy'.

The challenge, however, in appreciating Quantum Mechanics is not in following the logic, but in its astounding implications.

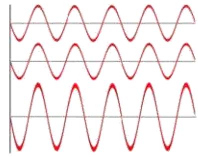
> Anyone who is not shocked by quantum theory has not understood it.
>
> *Neils Bohr, Nobel Prize winning quantum physicist*

Quantum Mechanics adds significantly to the search for a Theory of Everything, but in the process also vastly enlarges the puzzle, posed by Relativity, about the unreal nature of perceived reality.

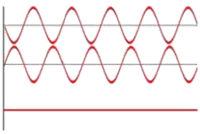
Before We Start, A Few Simple Concepts

Interference, or how to add up waves

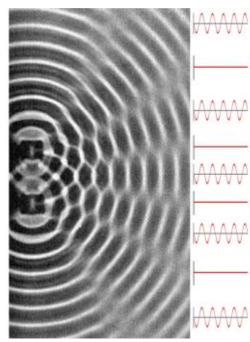
We know how to add up numbers. Adding waves is almost as easy.



At right, the top two waves are in step. When they meet, they '**interfere constructively**' to form a wave whose height equals the other two added together, as the third wave shows.



At left, the top two waves are out of step. When they meet they '**interfere destructively**', and the resulting wave height is flat.



Two pebbles dropped into calm water produce ripples. These two radiating waves interfere with each other constructively and destructively, as at right. The result is an alternating pattern of waves / no-waves, which shows up as stripes at the right-hand edge. It is a signature pattern produced only by interfering waves.

Mathematical descriptions and interpretations

Physicists usually first visualise how the universe works and then develop the supporting maths. Sometimes that doesn't work, so they try looking for a mathematical description of observations, which they then try to interpret, or visualise. For example, zoologists tracking changes to the tiger population discover a mathematical description of 10% decline per year. While this is not an explanation for the changes, it helps direct the search.

Consider a series of numbers from 1 to 10. We eventually conclude it is a random series. This is a mathematical description which directs our search for how they were produced. It might be the number of heads (or tails) from many sets of 10 coin tosses, or numbers drawn from a hat. These are just possible 'interpretations' of the mathematical description until each is proved or disproved.

Quantum Mechanics Over A Cup Of Coffee

Is it a wave, is it a particle?

On page 49 we saw briefly that light could be perceived either as a wave or, as Einstein suggested, a particle called a photon.

> It seems to me that the observations associated with … the emission or transformation of light [such as photoelectricity] are more readily understood if one assumes that the energy of light … is not continuously distributed … but consists of a finite number of energy quanta* which are localized at points in space, which move without dividing, and which can only be produced and absorbed as complete units.
>
> *Albert Einstein*
>
> * 'Quanta' is the plural of quantum.

By 1923 there was conclusive experimental evidence backed up by sound maths for both the wave and the particle theories of light. Unfortunately, the wave theory could not explain light's particle-like behaviour and vice versa. The solution to this conflict, known as '**wave-particle duality**', led directly to a new branch of physics, Quantum Mechanics.

Soon after 1923, it became clear that it wasn't just light which exhibited 'wave-particle duality'. The tiny particles which make up atoms, e.g. electrons, also exhibit this weird double life. But atoms are the building blocks of solid matter. How could the tiny indivisible particles which make up solid atomic matter sometimes behave like a wave that spreads out over a volume of space?

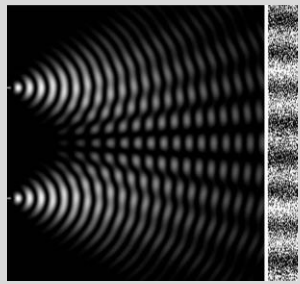
It also became clear that in some experiments light or sub-atomic particles exhibit wave-like behaviour while in others they exhibit particle-like behaviour. It is as if light, or our tiny particles of matter, somehow choose how to behave according to the type of experiment in which they are being observed.

The 'double-slit experiment' is just one of many which demonstrates this schizophrenic behaviour, see box on next page.

Leading a double life, the double-slit experiment

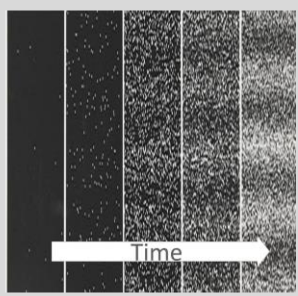
This experiment demonstrates wave-particle duality, and also that an individual electron particle can appear to be in two places at exactly the same time.

A narrow beam of electrons is projected through a single slit at a screen. Unsurprisingly, we see a single white stripe on the screen. If, instead, the electron beam is fired at two slits (as at the very left in the top image) we'd expect to see two stripes on the screen, one for each slit.



But what we actually see is a pattern of many stripes (as at the very right of this image), the signature pattern of interfering waves. We can't actually see the wave interference shown in the main part of the image, but we must infer its presence from the signature pattern, and must conclude that the electrons are behaving as waves.

Now, let's slow the experiment right down so that, instead of a beam of electrons, just one electron at a time is fired at both slits. We can do this by turning down the power in our source until, like a dripping tap, it has just enough energy to release one electron every second. In this situation, we might expect a different result.



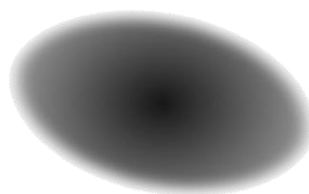
What we see, however, is shown in the series of screen images in the second picture. Individual electrons hit the screen, each leaving a particle-like point. Not only that, but we see them hit the screen in many different locations, and, over time, they build up exactly the same signature interference pattern of white stripes. In fact, in exactly the same way as the stripes in the first picture can be seen to be made up of individual points when you look closely. This can only mean that each electron must somehow be passing through both slits at the same time and then somehow interfering with itself.

In other words, each apparently indivisible electron particle is behaving like a wave as it journeys through both slits, and then appears again as a single particle when we observe it at the screen.

A mathematical description of wave-particle duality

Light also displays wave-particle duality in double-slit experiments, just as particles do. But how can particles behave like waves and vice versa? How can particles be in two places at once? Confused, physicists looked for mathematical descriptions of the observations. They would worry about the physical interpretation later.

They developed an equation, called a **wavefunction**, which describes the *probability* of finding a given particle at any point in space. For a single unconstrained and unobserved particle the wavefunction gives it an equal chance of being *absolutely anywhere* in 3D space at any instant. As constraints on the particle increase, such as the presence of other particles, the available space for our particle narrows. So, the probability of finding it in that narrower space increases, while decreasing everywhere else. In this way, the wavefunction paints a picture of our particle in which it is spread out in space. And, with this somewhat abstract description, our particle's possible location can be either wave-like (many places at the same time) or particle-like (when constrained to a very narrow space). Ultimately, when the electron interacts with something else (e.g. observed) its wavefunction is said to '**collapse**' to a specific particle-like location.



Let's apply this idea to the double-slit experiment. When the particle sets off we know its precise location, and likewise, when it leaves its point-like imprint on the screen. Unobserved between these two points it is in many places at the same time, with varying degrees of probability. And it is this wave-like state which passes through the two slits producing the signature interference.

This seems weird. How can an electron or photon be wave-like one instant and particle-like the next? By way of partial analogy, imagine a tossed coin. As it spins it is possibly heads *and* is possibly tails at the same time. But when caught and observed it is randomly clear which state it is exhibiting, heads *or* tails.

Uncertain times

Even when the wavefunction collapses to a specific state a particle's position and speed cannot both be precisely known at the same time. Greater certainty of one means less certainty of the other.

This is not due to issues with the measuring equipment. (There is always a so called 'observer effect': disturbance in the position or speed of tiny particles when measurements are made.) No, the cause of the Heisenberg '**Uncertainty Principle**' (named after its originator) goes deeper. It's a similar problem to trying to describe a swinging pendulum's speed and position. To know its speed we must let it swing, but then its position is changing and uncertain. Conversely, if we know its position, its speed at that same instant can't be known since we don't know how wide the swing is.

There is another surprise. If we can't know a particle's present position and speed precisely, we cannot calculate its past or future trajectory with precision. Our knowledge of the past or future becomes more uncertain as we distance ourselves from the present. We must conclude that, despite our perception of reality, we cannot know anything with absolute certainty.

Fickle Nature

Could Nature really be so unpredictable? Consider the behaviour of radioactive materials, first observed in the 1890s. Made of millions of atoms and inherently unstable, these decay to stable atoms in a predictable way: a precise proportion decay in a period of time. But the precise moment any single atom will decay is unpredictable. Quantum Mechanics explains that, while the decay process in any one atom is random, the probability inherent in the wavefunction leads to statistically predictable behaviour in a collection of atoms.

So, returning to our coin analogy, just as we can't predict the toss of an individual coin, we do know that on average 100 tosses will yield 50 heads. Radioactivity, it turns out, is Nature's demonstration that it, Nature, is inherently random.

Many possible interpretations of reality

The undisputed maths describes perfectly the experimental observations of sub-atomic particles. When first formulated, no one presumed it reflected the physical world. However, the quest for the physical interpretation of apparently collapsing wavefunctions sparked passionate disagreements which are on-going today.

Some suggested that while the maths worked, maybe it was missing some '**Hidden Variables**', which, when added would remove the unpredictability of a particle's location. This incompleteness idea has been largely discounted by experiment.

Another interpretation, known as the **Copenhagen Interpretation**, is that wavefunction collapse is actually the complete description of reality. That Nature is inherently unpredictable at this small scale, and hence unknowable. This does, however, raise another awkward question. Precisely what does or does not constitute an interaction which can trigger this collapse?

Another interpretation avoids the need for the collapse of wavefunctions altogether. It argues that instead of collapsing into just one state, each particle continues into all possible future states. In this '**Many Worlds Interpretation' (MWI)**, a 'multi-verse' of parallel worlds comes into existence, each invisible to all others. When proposed in 1957, MWI was largely ignored. Now, in straw polls, roughly half of physicists find MWI has merits, though with a range of opinion as to how real or unreal these other universes are.

There are other interpretations. Many are versions of those already mentioned. As yet, there is no conclusive proof that any one interpretation is the right one.

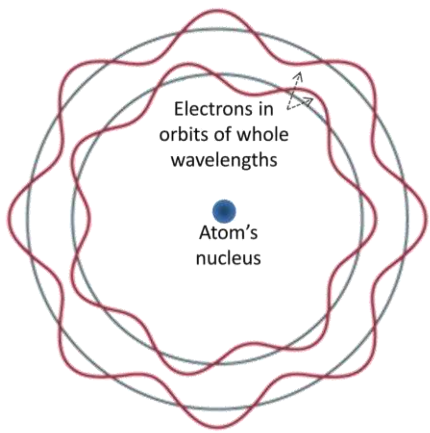
As we've said, the mathematical description of collapsing wavefunctions may not be the right explanation. Nonetheless, it explains observations and is used by engineers to build not just today's computers but, very soon, even more powerful 'quantum computers'. Furthermore, as we'll see, Quantum Mechanics helps explain how energy is organised into the material world we observe.

WHY WE DON'T FALL THROUGH THE FLOOR

Quantum Mechanics provides the underpinning physics which helps explain what stuff is made of, how energy is organised to create solid matter. Given that the particles which make up atoms account for less than 0.1% of its volume, how is stuff so solid? Why don't we just fall through the floor?

Using Quantum Mechanics, physicists have developed a '**Standard Model**' which describes the building blocks of matter and of all the forces we experience, except gravity.[11]

For example, let's consider electrons inside an atom. Firstly, since they are all negatively charged, they repel each other, keeping their distance one from the other. And, secondly, while drawn to the positively charged nucleus, the wave-like nature of their wavefunctions constrains their vibrations to orbits of a size which allow only completely joined up waves, as in the diagram. (This results from constructive interference. Orbits which don't form complete waves, interfere destructively, and cancel out; the same principles which produce the stationary waves we observe in a whipped skipping rope.)



It is this field of energy from many electrons, spread out in specifically defined orbits defined by their wavefunctions, which gives substance to atoms. Much as force-fields provide defensive shields to sci-fi space ships. It's why we can't fall through the floor.

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[11] The Standard Model also includes things called '**bosons**' which transmit forces. For example, photons are bosons which transmit the electromagnetic force, such as light. Other bosons transmit nuclear forces which help bind protons, neutrons and electrons together to form atoms. And the most well-known, the '**Higgs Boson**', imparts the property of mass to particles.

Why don’t mountains appear and disappear?

In everyday life we don’t see large objects behaving as if they could be anywhere or everywhere at the same time. So how do microscopic particles which can be in many places at the same time assemble themselves into the large scale predictable reality we observe?

The explanation is that the large scale reality we observe is made up of (a) many individual instants in time, and, (b) many particles. What that means in our everyday reality is as follows.

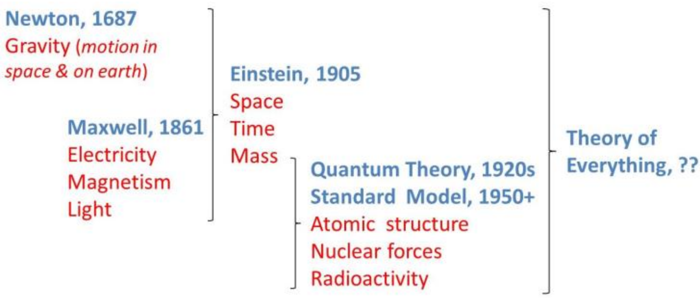
(a) Something interesting happens when the rules of Quantum Mechanics are applied to a single particle over many instants in time. The potential for random behaviour in one instant is partially negated by its potential for random behaviour in the next several. In more technical terms, the wavefunction interferes with itself over time.

(b) When a number of particles come together into atoms they constrain each other’s scope for random behaviour; much like constraining a hyperactive dog in a small space.

In this way the sub-atomic particles which obey the laws of Quantum Mechanics take on the predictable characteristics observed of bigger objects over longer time periods. This is known as the ‘**Correspondence Principle’**, which states that at larger scales the quantum laws of small-scale physics must correspond with (i.e. produce the same answers as) those of classical physics.

THE SEARCH FOR A THEORY OF EVERYTHING CONTINUES

The search for a 'Theory of Everything' unifying Relativity and Quantum Mechanics is on-going. As we've seen, the Standard Model includes all the building blocks of matter and an explanation for how they interact with all natural forces, except for gravity.



But significant differences exist between Relativity and Quantum Mechanics which make this search for a unified theory difficult. These differences are so fundamental as to even lead some to question whether there is something wrong with these otherwise well-proven theories.

Relativity's equations	Quantum Mechanics' equations
Continuous and smooth universe	Quantum packets (lumps) of energy
Events (pre)determined by laws	Events determined by probability
'Local' bubbles of reality	'Non-local' [12]

The search for a Theory of Everything takes physicists to one of the frontiers of physics, black holes. Gravity, a much weaker force than electromagnetism or the nuclear forces which bind atoms, has an exceptionally limited effect on particles of tiny mass. Things are different, however, in a black hole. In this very small yet massively

[12] Quantum Mechanics says a particle is possibly in many places at the same time. Then, when its wavefunction collapses, it is instantaneously in one place and nowhere else. This synchronised change in very distant probabilities means the quantum universe is 'non-local'. Experimentally proven (by 'entanglement', see page 103) it provides proof of Quantum Mechanics. (NB This instant change doesn't infringe Relativity's speed limit, 'c', since information isn't transmitted.)

dense volume, the gravity produced by this vast mass can have a discernible influence even on tiny particles. Here the force of gravity and the other forces of Nature all operate at the same scales. And so here, maybe, a means of combining Relativity and Quantum Mechanics can be discovered through a 'quantum explanation of gravity'.

The main attempts revolve around finding a quantum-scale description of space-time itself. Many different ideas have been put forward. One for example is based on the concept of '**strings**'. These are theorised to be incredibly short one-dimensional pieces of energy. Another is based on the idea of some sort of fluctuating '**quantum foam**'.

THE FIGHT FOR THE NATURE OF REALITY

The different interpretations of wavefunctions reopen debates over the nature of reality.

Is seeing far more than just believing?

Quantum Mechanics indicates that the electron's choice to be wave-like or particle-like depends at the very least on interaction with other particles in its environment. Not only that, but, the type of experimental observation being made determines outcomes. '*Reality is in the observations, not in the electron*,' says physicist, Paul Davies.

It is perhaps unsurprising that if we close one slit in the double-slit experiment the signature interference disappears. But this is also true if all we try to do is observe which slit an electron passes through. Our act of observation triggers wavefunction collapse and, no longer wave-like, our particle goes through only one slit.

Many questions ensue. Is particle interaction sufficient to trigger collapse or is 'observation' required? If observation is required, as some believe, what takes place between the 'observer' and the 'thing observed'?

And, is the observer's purposeful intent required, i.e. consciousness? The role and consciousness of observers in our apparently unpredictable reality is much debated and opinions vary.

To be or not to be dead and alive

Erwin Schrödinger (who came up with the wavefunction in the first place) was unhappy with the interpretation that Quantum Mechanics was unpredictable and that observers might matter in producing wavefunction collapse. By way of demonstration, he invented a hypothetical cat enclosed in a box which also contained a randomly-timed means of causing its death. According to this interpretation of Quantum Mechanics, he ridiculed, **Schrödinger's cat** is supposedly both alive and dead until we open the box to check on its health. At this point the wavefunction supposedly collapses and we see either a living or dead cat.

Einstein was as disturbed as Schrödinger by the implications of Quantum Mechanics. He added to the cat's troubles by asking if a conscious cat might be aware that it was both dead and alive, or whether that level of self-awareness might trigger its own wavefunction collapse! The idea of such an unpredictable universe appalled Einstein. Referring to God, he said, '*I am convinced He does not play dice with the universe*'. However, experiments reveal that both Schrödinger and Einstein were wrong, and that the quantum world is indeed an unexpectedly strange place.

To be … or not to be so sure

For centuries the universe was regarded as '**deterministic**' in which particles, guided unequivocally by laws of physics, reach predictable futures. Wavefunction collapse questions the foundations upon which physics is built. Our universe, it implies, is not deterministic. It is at best *statistically* predictable.

The many worlds interpretation we met earlier sidesteps this problem since all future worlds are determined by present worlds. But the very idea of many parallel worlds confronts our sense of reality at least as much. However, until there is proof either way, we should at least bear in mind that it was only in the last 100 years that we discovered that ours is not the only galaxy.

It is as if, with the inherent uncertainty of Quantum Mechanics, Nature has placed a protective veil of unpredictability over its ultimate secrets. Once again, our evolution-constrained senses mislead our perspective of reality. This time it is from our lack of everyday experience of the microscopic scale. If we lived at that scale, we would see particles behaving unpredictably, neither here nor there, yet everywhere. And we would think it perfectly normal.

LIFTING THE CURTAIN OF REALITY

We started this chapter with Neils Bohr's quote that, '*Anyone who is not shocked by quantum theory has not understood it*'. If this brief overview of the weirdness of the Quantum world has left you a little enlightened and a lot bemused, you are in good company.

> Anyone who says that they understand Quantum Mechanics does not understand Quantum Mechanics.
> *Richard Feynman, Nobel Prize winning quantum physicist*

We've discovered that Mother Nature is inherently random. Only time will tell if we'll ever be able to peer fully beneath her mysterious veil of quantum unpredictability.

A REMARKABLE 150 YEARS

The 1800s saw the advances of Electromagnetic Wave Theory and Thermodynamics (the physics of heat, see page 89). The 1900s heralded Relativity, Quantum Mechanics and the Standard Model. These new ideas helped completely transform Man's view of the world he inhabits. Newton's Mechanics had ruled alone for the 150 years preceding all these advances.

Presuming this exponential rate of discovery continues we can only try to imagine what the next 150 years will bring.

Chapter
On 'Time'

Time, Not What It Seems

> Put your hand on a hot stove for a minute, and it seems like an hour. Sit with a pretty girl for an hour, and it seems like a minute. That's relativity.
>
> *Albert Einstein*

Einstein was clearly sharing a joke, but one with a point, highlighting our highly variable perception of time. He invites us to question that perception; to stand not in the rushing waters of time's river but to view it from above and try to comprehend the whole river. After all we've seen how different to everyday impressions time actually is.

- Time is not absolute: it is not the rigidly constant rhythm we perceive, it is personal, slowing as relative speed increases.
- Time is not universal: it is not the same time everywhere, as our tram-riding Einstein discovered.
- Time has not existed forever: it had a beginning, created with the universe as part of the Big Bang. There was no 'before'.
- Time is not that special: it's just one dimension of space-time.

The Problem Of Time

Despite Relativity's insights, the question 'What is time?' continues to trouble physicists and philosophers as it has for millennia.

The problem with infinite time

In his 1871 *Critique of Pure Reason*, philosopher Immanuel Kant described the implicit contradictions of time stretching infinitely into the past and future. If the universe had been created, he said, what made it wait an infinite time before coming into existence? On the other hand, if it has been around forever, everything that could happen will have happened, and the universe would have ceased to exist.

We perceive time as flowing from the past to the future. So, the question arises, does time actually flow? If not, why does it *appear* to flow (while space just 'is', or appears to be)? And why in only one direction, compared to space in which we travel in all directions?

There are other questions too. What is the present? Why is it that we are only conscious in what we perceive as the 'present' (and not in the 'past' or 'future')?

Perspectives On Time

While what time actually is remains a mystery, there are some commonly agreed views.

The 'here' and 'now' of it

We've seen that space and time were created by the Big Bang. And, since we perceive *all of* 'space' to be all around us (forwards & backwards, up & down, left & right), then presumably *all of* 'time' must also be all around us (before, now, after). Crazy! Surely?

> People like us, who believe in physics, know that the distinction between past, present and future is only a stubbornly persistent illusion.
>
> *Albert Einstein*

In everyday speech 'here and now' conveys certainty. But we understand that that certainty has limits. Even when using the word 'here' whilst talking to a distant person by phone, we understand that 'here' could mean theirs or mine, apparently depending on who is speaking. But we've all had conversations which include the phrase, 'When you say *here*, where do you mean?'

Likewise, their 'now' is as real for them as mine is for me. But I won't observe their 'now' until light from their present has taken a finite time to travel to me – sometime in my future. And as that light continues on its journey in the universe it will maintain that record of their 'now' forever, into what I regard as the future.

This sounds like playing with words. But remember that Einstein demonstrated that there is no such thing as universal or absolute time. So which point on 'now's' path can we say is the real 'now'? We must contemplate that, all possible 'nows' exist somewhere in space-*time*, just as all possible 'heres' exist somewhere in *space*-time. And, since all possible 'heres' constitute all of space, so all possible 'nows' must constitute all of time; as we'd expect of a Big Bang which brought all of space *and time* into existence, *in the same instant*.

> Any real body must have … Length, Breadth, Thickness, and Duration. But through a natural infirmity of the flesh … we … overlook this … because it happens that our consciousness moves intermittently in one direction along the latter from the beginning to the end of our lives.
>
> *H. G. Wells, The Time Machine, published in 1895*

It appears that Relativity, this successful description of Nature, does not distinguish between past, present or future, despite we humans apparently requiring these notions. Not only that but, if all of time exists, what does that mean for our sense of cause and effect or of free will?

It's tempting to ask, if all of time exists, whether travel through time is possible in the same way as travel through space. But many of the same problems still arise. For example the '**grandfather paradox**', in which I travel into the past to kill my grandfather before he gives birth to my mother or father! Or why people from the future have not visited us (unless they have already without our realising)?

Is 'change' what we interpret as time?

This discussion about 'here' and 'now' led Einstein to the following thought.

> The only reason for time is so that everything doesn't happen at once.
>
> *Albert Einstein*

We might more fully appreciate the idea behind his statement, by considering this alternate proposition: the only reason for space is so that everything doesn't happen in the same place! Put another way, if nothing ever changed or happened in the world around us then there would be no moment-to-moment differences to observe. And, arguably, without these moment-to-moment differences, we would have no concept of 'moments' themselves, and there would be no need for time. We might then feel safe in asking if time has an existence independent of events? This idea gains weight given Relativity's insight that time is not separate to the universe but was created with, and is a part of, the universe.

Perhaps, therefore, time doesn't actually 'flow'. Maybe it's just a perception, the means by which we distinguish and describe one small change from the next. This is not dissimilar to one of Zeno's Paradoxes which challenges our view of motion. This paradox asks whether an arrow in flight is actually moving at any given instant.

The one-way flow of time

Why we perceive this flow real or otherwise in only one direction, past to future, baffled physicists until the mid-19th century because no known law of physics requires time to be directional.

Consider the simple equation:

SPEED equals DISTANCE divided by TIME

Nothing about this equation requires time to be a positive number. Time could be a negative number (denoting time going backwards) and the equation still works, even if we find it hard to translate the answer into everyday concepts. So, if the laws of physics do not restrict time to one direction, why do we perceive time as irreversible? The answer turns out to have nothing to do with Relativity and everything to do with probabilities.

A tidy pile of bricks can be easily knocked over. But we can't imagine those knocked-over bricks reassembling themselves into a pile. It takes more work, or energy, than it took to knock the pile over. It's not impossible for the bricks to reassemble themselves, just highly improbable. It would require other objects or even atoms to act in unison on each and every brick in just the right way to encourage them back into a tidy pile. But what freely moving objects or vibrating atoms actually do is collide randomly with other objects or atoms giving up some energy to those which are moving less. As a result, over time, the statistically likely outcome is that all objects and atoms reach energy equilibrium with each other.[13]

This tendency towards disorganised states is called '**entropy**' and imposes itself across the universe. It is why we observe events unfolding in only one direction. 'Past' and 'future' are distinguished by this statistically more likely transfer of energy. This so called '**arrow of time**' is accepted physics. Beyond that is speculation.

Some believe that time's arrow might be linked to the expansion of the universe. As it expands, it thins and cools, its energy gradually dissipated evenly throughout the universe. Without any energy differences providing the motivating means to do work, order cannot be created; our universe is like a heart monitor gradually flat-lining. Some physicists go further, suggesting that the expansion of the universe is also why we perceive time to be flowing at all; as if we're in a region of space-time where we perceive the dimensions of space as all around us, and the dimension of time as rushing past.

The shape of time

Space-time came into existence with the Big Bang. There is no 'beyond' outside the universe, whether space or time. It started with the Big Bang, there was no 'before'. This might have pleased Immanuel Kant with whom we started this discussion on page 85.

Space-time is a complete whole, the 4D equivalent of the surface of a ball, comprising all of space and time. Upon this surface, energy-density varies from low (empty space) to very high (black holes). And so too, due to gravitational time dilation (see page 56), does the rate at which time passes vary, and in black holes it even stops. Time is not the infinitely smooth timeline which our intuition perceives.

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[13] The vibration of atoms is what we experience as heat. The part of physics, which relates heat to other types of energy is called **Thermodynamics.**

Chapter

RELATIVITY'S PHILOSOPHICAL IMPLICATIONS

This chapter touches upon some of the philosophical implications of Relativity and Quantum Mechanics. These ground-breaking advances in 20th century physics shine some new light on age-old questions.

THE LIMITS OF PERCEPTION, HOW MUCH DO WE REALLY KNOW?

The Alice in Wonderland nature of length contraction, slowing time, and the surprises of space-time force us to confront the fact that our everyday experience is confined to less than one millionth the speed of light. And Quantum Mechanics further challenges our insufficient macroscopic senses with the random uncertainty of the small scale atomic world. That our senses can so mislead us forces the realisation that they are evolution-constrained for survival in a low-speed, large-scale world.

> Our best theories are not only truer than common sense, they make more sense than common sense.
>
> *David Deutsch, Physicist*

If such evolution-constrained senses lead us to be so unaware, then we must forever be conscious not just of our limitations, but that we may not even know what those limitations are. To disbelieve just because it is not what we 'expected' is an arrogant naivety; albeit a flaw which we humans are prone to demonstrate.

This dependency on our unreliable senses brings to mind Plato's allegory of the cave, a cave in which people are forever captive. In this allegory, they can see only shadows of reality cast onto the cave's walls. And so these shadows become the cave-dwellers view of reality, their perceived reality. We are, in the same way, prisoners of our somewhat deficient senses.

How Real Is Reality?

Given these sensory deficiencies it seems reasonable to ask, just what is ‘reality’?

Added weight is given to this question by the Uncertainty Principle’s implication that there is no such thing as absolute certainty. Quantum Mechanics further demonstrates that observer and thing observed are interdependent. Some suggest that reality exists only when observed. Some people ask the further question, does the thing doing the observing need to be conscious? A version of the well-known question, ‘If a tree falls in a forest and no one is around to hear it, does it make a sound?’

I Do Mathematics, Therefore I Am

There are those who would take this logic one step further. If our description of the universe through Relativity and Quantum Mechanics is so reliant on complex maths, then is *what* we perceive dependent in some way on the *form* of the mathematics we’ve invented?

This leads to an uncomfortable choice. Would we perceive the universe differently if we invented a different form of maths? It feels safest to presume this can’t be right. After all, the maths we have invented works so well at explaining our world experience.

In which case mathematics must in some way be fundamental not just to a description of the universe, but to the universe itself! This would mean that we did not invent maths, we discovered it.

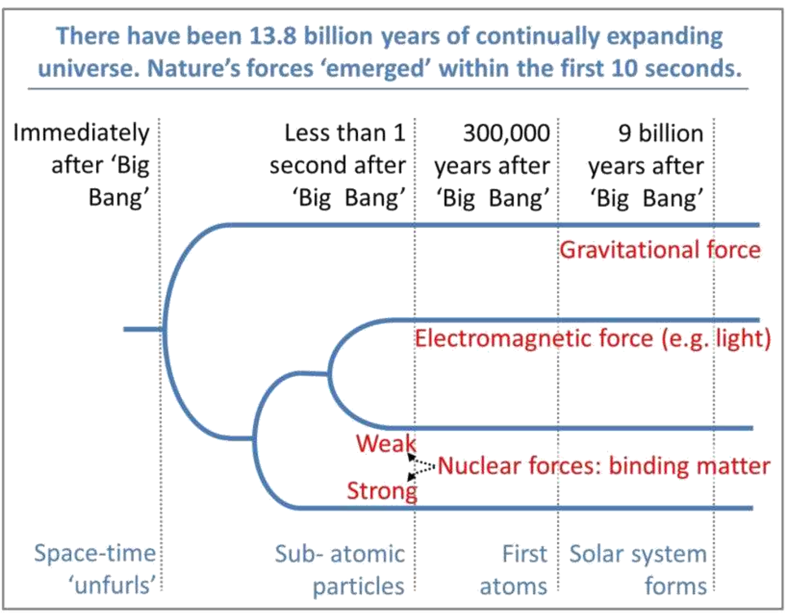
But if mathematics is fundamental to the universe, it would have had to exist at the time of the universe’s creation. Paradoxically, this presumably includes the creation of the mathematics and physics required to design the universe in the first place.

We might also ask if we and all we experience are just the result of complex calculations by an enormous computer we can’t perceive. And if so, would we ever know it? Much as a computer game character can never know that it is a virtual creation.

IN THE BEGINNING, SOMETHING FROM NOTHING

On page 60 we described how the universe exploded into existence from a singularity, through a 'Big Bang'. As science writer Marcus Chown puts it, '*Everything – space, time, energy and matter - came into being in the Big Bang and began expanding everywhere at once*.'

The Big Bang theory also draws upon Quantum Mechanics, whose probabilistic nature permits tiny random energy fluctuations even in the seeming void which preceded the Big Bang. These fluctuations snow-balled almost instantaneously into a vast explosive disturbance releasing enormous quantities of electromagnetic energy, all in the first fractions of a second. In turn, courtesy of $E=mc^2$, the sub-atomic particles that would eventually become matter began to form. Something from seemingly nothing.



In the immediate aftermath of the Big Bang powerful processes gave rise to space-time, energy and matter. Along the way it also gave rise to the family of Nature's forces. (By way of comparison, the earth is 'only' 4.5 billion years old, and our human ancestors appeared barely 200,000 years ago.)

Some models of the origin of the universe suggest that in the miniscule fractions of a second after the Big Bang, time was exactly like a dimension of space, but very soon after, it unfurled into the dimension we now experience as time.

‘What came before the Big Bang?’ is not an easy question; since, if there was no time, there can be no ‘before’. Professor Stephen Hawking explains that that’s a bit like asking, ‘*What’s north of the North Pole?*’ Equally, ‘Where was that singularity?’ or ‘What is space-time expanding into?’ are not easy questions either: the answers ‘Nowhere’ and ‘Nothing’ are insufficiently satisfying. It is here that we meet, again, the limits not just of the universe, but of our current understanding.

> In the beginning the Universe was created. This has made a lot of people very angry and been widely regarded as a bad move.
>
> *Douglas Adams, A Hitchhiker’s Guide to the Galaxy*

The Design Of The Universe

In this Big Bang theory the universe can bring itself into existence by virtue of the laws of physics. Once again, we must ask, where did those laws come from? Did scientists *discover* them, or did they *invent* a version that works at explaining the universe?

The conundrums don’t end there. As we’ve seen, the speed of light ‘c’ plays a fundamental role in the structure of the universe. This universal speed limit, one of nature’s constants, establishes the relationship between space and time, and between energy and matter. It is awe-inspiring and humbling to peer into the very design of the universe in this way. But the existence of this constant, and many other important constants like it, yet again begs the question, where and when did they arise?

To highlight the concern, physicist Arthur Eddington asks us to imagine a sculptor’s claim that the form of a human head lies within a block of stone. Incredulous, we watch as he hammers and reveals. Was *this* head there before? What if he’d made the nose longer?

What if the finely-tuned relationships between the various universal constants were just marginally different? Might the universe and all the life in it be unrecognisably different, or indeed have not come into existence at all? This is known as the '**Anthropic Principle**'. In its extreme form it suggests that the universe exists only to bring us, human observers of the universe, into existence! This seems a very self-centred interpretation, reminiscent of the belief held for millennia: that the Earth is the centre of the heavens, and that Man is the purpose of all Creation.

> We are just an advanced breed of monkeys on a minor planet of a very average star. But we can understand the Universe. That makes us something very special.
>
> *Professor Stephen Hawking, Physicist*

If we do have a special place in the universe, how are we to make sense of that? To some, the many-worlds interpretation of Quantum Mechanics provides a clue. If there are many parallel universes, all invisible to each other, Mankind will come into being only in the tiny subset of these universes in which conditions are favourable. And, unable to see the other parallel universes, Mankind will consider himself special. Much as a toddler who has not yet developed a 'Theory of Mind' perceives only its own importance.

CHANCE? QUESTIONING HUMANS

The recurrent appearance of 'Chance' in physics' recent advances is thought-provoking. We have the statistical determinism of Quantum Mechanics (page 83), the statistically mandated direction of time (page 88), and the 'Anthropic-ally' fortunate alignment of universal constants (this page) which gave rise to the universe, to human existence, and to our nature of questioning Nature.

What does it all mean? Does it need to mean anything, or is that just the way things are? Possibly? Probably?

FREE WILL?

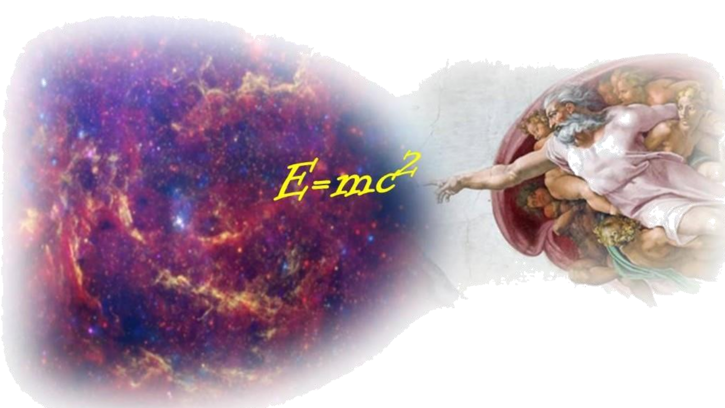
The earlier discussion on the nature of time, in *On 'Time*', leads to an inevitable question. If all of time is already laid out around us, just like space is, then surely future events, just like past events, are all laid out, i.e. predetermined. This is where the cutting edge of physics meets the timeless discussion of philosophers: who are 'we', what does it mean to 'experience', and do we have 'free will'.

Personally, I can't imagine that we humans do not have free will. But then maybe I was always destined to say that! Perhaps our instinctive belief in 'free will' will be validated when the seeming determinism of Relativity is finally unified with the statistical determinism of Quantum Mechanics.

ALL MIGHTY?

When we consider the laws of physics we describe them as: 'universal', 'absolute' and 'inviolable'. These are similar terms which (some) humans use to describe an omnipotent God. And, let's not forget also that an omnipotent God is also often accused of undermining humankind's sense of 'free will'.

Relativity points to a different description of the universe than that proposed by religion and its traditional perspective of God. But, given where Relativity and Quantum Mechanics have led us so far, we might imagine that if there is a God then He or She is almost certainly a mathematician!



Chapter

Relativity, Culture And Society

This chapter takes a very brief look at some of Relativity's wider influence on human thought.

Sparking Imaginations

Relativity was largely unknown outside the scientific community until the 1919 experiment that showed starlight could be bent by gravity. In confirming Einstein's theory that space and time were not absolute it shook the very foundations of beliefs Mankind had held since time immemorial. As such, it made front page news worldwide. And it seeped into the imaginations of thinkers and creative spirits across diverse fields.

Ideology

We have seen already that proponents of Relativism wrongly deployed Relativity as proof of their point of view that nothing at all was absolute (see box on page 62). But others also employed Relativity to support their ideas.

There were those who interpreted the almost purposeful laws and constants of physics as a demonstration of the universe's divine spirituality.

At the other extreme, some Soviet physicists argued that Relativity's emphasis on reality as it really exists supported a Marxist materialist agenda, rather than the idealised sense of reality which we as humans perceive.

And 'logical positivists', who believed that logic applied to empirical evidence was the sole means by which to arrive at scientific truth, deployed Relativity in support of their views.

Relativity was a bandwagon on to which many people climbed. By and large it seems that Einstein did not appreciate all these fellow travellers.

> I am not a Positivist. Positivism states that what cannot be observed does not exist. This conception is scientifically indefensible, for it is impossible to make valid affirmations of what people 'can' or 'cannot' observe. One would have to say 'only what we observe exists,' which is obviously false.
>
> *Albert Einstein*

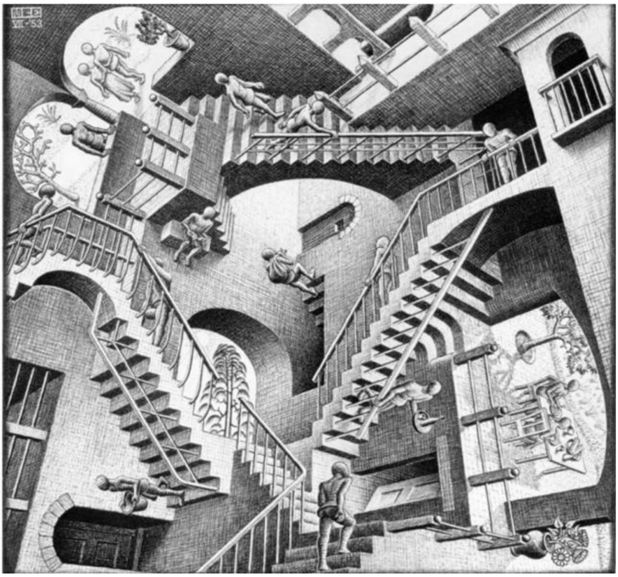
The worst ideological abuse was the attack on Relativity on the pseudo-scientific grounds that it was manipulative 'Jewish Physics'. This occurred primarily in Germany in the years between World Wars I and II. While Einstein and his Relativity bore the brunt, this accusation was also attached to Quantum Mechanics, the development of which involved some Jewish physicists. The anti-Semitic narrative branded the new physics of Relativity and Quantum Mechanics as antithetical to the principles and supremacy of Aryan beliefs. And a perfect storm of factors gave this narrative momentum: the petty jealousies of a reasonably high profile German scientist, combined with a rising tide of populist opinion, and the adoption of this narrative by the Nazi regime in furtherance of its propaganda and increasingly abhorrent actions.

Art And Literature

A so-called 'Modernist' movement had been accelerating from the 1850s, rejecting the certainty of earlier Enlightenment thinking. It appealed to innovators to 'Make it new!' in all walks of life and lasted well into the 1900s.

Relativity's later arrival is of course not a response to that appeal. But strong arguments can be made for the influence which Relativity had on Modernists. The case here is not that Relativity added momentum to Modernism, but that the uncertainties of space and time provided a theme which could be used in art and literature.

As such, Relativity influenced many styles such as Dadaism and Surrealism. *The Disintegration of the Persistence of Memory* by Salvador Dalí is one example widely cited in which the relationship between mass, energy, space, and time were explored, though Dalí himself denied this influence. MC Escher's work, *Relativity,* is another example showing the complete dislocation of space.



Relativity
by MC Escher

More recently, artists such as Anish Kapoor have explored humans' psychological disassociation with space and time caused by extreme darkness. Some of his works place people inside a completely matt black, dark space. Any notion of space will eventually disappear as they lose all sense of physical reference points or objects. And, since time is perceived as the progression of events, he proposes they lose all sense of time also.

The subjective nature of time was also taken up by writers. For example, Kurt Vonnegut in *Slaughterhouse 5* gave a capacity for time-travelling to an alien species as a means of understanding the character of his all-to-human protagonist.

> All moments, past, present and future, always have existed, always will exist. The Tralfamadorians can look at all the different moments just that way we can look at a stretch of the Rocky Mountains, for instance. They can see how permanent all the moments are, and they can look at any moment that interests them. It is just an illusion we have here on Earth that one moment follows another one, like beads on a string, and that once a moment is gone it is gone forever.
>
> *Slaughterhouse 5, Kurt Vonnegut*

GOING NUCLEAR

Mass-energy equivalence, as described by $E=mc^2$, pointed to the new horizon of the nuclear age. Quantum Mechanics provided the tools which enabled engineers to realise that potential.

Within just a few decades it gave society a whole new set of moral concerns, which, to all but the firm of one opinion or other, usually present themselves as dilemmas.

Can the use of atomic weaponry ever be justified if it shortens wars and ultimately saves lives?

If any one nation harnesses the power of atomic weaponry, is the building up of nuclear arms by others, and the principle of ‘mutually assured destruction’, the only realistic way to maintain world order?

Do the enormous investment and the potential risks involved in nuclear energy justify the seemingly always just out of reach promise of unlimited safe, clean power?

And, until we have sufficient ‘green energy’, how are we to weigh up nuclear energy’s true cost and risks against the true cost and risks of fossil fuels; taking into consideration risks to health and the environment and the associated long-term financial cost?

The ensuing debates seem to pit one person’s moral high ground against another person’s real world pragmatism, with no middle ground upon which either side feels able to compromise.

Within this frame, a new word has entered the popular vocabulary, ‘nuclear’. It carries a whole set of associations which often seem to inform public opinion (and hence political decision-making) more so than balanced risk assessment based on sound science.

Definition

going nuclear

Taking things to the absolute extreme in order to avoid a series of small escalations. This can be a way of winning a fight you might not otherwise win, but has the potential to destroy both people involved. *(From urbandictionary.com)*

Chapter

MORE ABOUT EINSTEIN

Einstein was '*unfathomably profound — the genius among geniuses who discovered, merely by thinking about it, that the universe was not as it seemed*'.

This is how TIME magazine explained why Einstein was their choice for 'Person of the 20th Century'. They continued that this choice was part due to the '*sheer brilliance*' of his work on Relativity, and part due to the work's '*far reaching implications*'.

It seems fitting that a magazine called TIME named Einstein as its 'Person of the 20th Century' given Relativity's insights into the nature of time itself.

WHAT MAKES EINSTEIN SO CLEVER? CREDIT WHERE CREDIT IS DUE

By 1905, when Einstein published his first paper on Relativity, a number of scientists had already thought of many of the things that Einstein thought and had created much of the mathematics that he would need. Indeed, Einstein himself reflected in 1953 that Relativity was '*ripe for discovery in 1905*'. A few scientists came within a hair's breadth of coming up with the Special Theory of Relativity before Einstein, most notably Henri Poincaré. This has led naturally to debate as to whether Einstein deserves all the credit he gets.

But these other scientists didn't arrive at Einstein's elegantly consolidated view of the universe. Primarily because they persisted in trying to make the theory and the maths fit old models, such as the existence of the ether. It is as if the majority of the scientific community treated Michelson-Morley's surprising observation of the invariance of the speed of light as a problem which had, somehow, to be fitted into their view of the universe. Einstein, on the other hand, started afresh with a blank sheet of paper; discovering in the process that the invariance of the speed of light, far from being a problem, was the key to a door behind which lay a whole new universe.

> Talent hits a target no one else can hit. Genius hits a target no one else can see.
>
> *Arthur Schopenhauer, Philosopher*

The ever more complicated mathematics of Einstein's peers appeared to be continually trying to patch things up. When Einstein published the self-evidently more elegant solution in his 1905 paper on Special Relativity, the portion of the paper dealing with the mechanics and mathematics of travel at or near the speed of light was just twelve pages long.

History's jury gives Einstein the credit. Hendrik Lorentz, himself significant in Relativity's early development, put it as follows:

'I considered my [work] only as a heuristic working hypothesis. So the Theory of Relativity is really solely Einstein's work. And there can be no doubt that he would have conceived it even if the work of all his predecessors in the theory of this field had not been done at all. His work is in this respect independent of the previous theories.'

Hope for us all?

Einstein's younger sister apparently found the young Albert to be a bit dreamy and slow. His parents, according to Einstein himself, '*were worried because I started to talk comparatively late, and they consulted a doctor because of it*.'

However, the myth that he did poorly at school is, just that, a myth. In fact, throughout his school career he did very well, rebelling only against the 'by rote' nature of learning. An early sign, perhaps, of his questioning nature.

BUT HE WASN'T ALWAYS RIGHT

Einstein deserves his elevated place in the history of ideas. But by way of cautionary note, no one is infallible. Here are a few things which he might prefer forgotten.

- Einstein initially resisted his own equation's conclusion that the universe was expanding, and forced an ad hoc 'cosmological constant' into them so that they described a static universe. In later years he apparently described this as, '*the biggest blunder*' of his life.
- Despite developing the ideas that lay behind 'space-time' in 1905, Einstein initially felt that space-time models and the mathematical tool of 'space-time diagrams' developed by Herman Minkowski added little of value to the physics. By 1915 Einstein was using these ideas. (See *A Little Bit Of Maths*.)
- Einstein argued against the idea of space-time singularities such as those required by the Big Bang or subsequently found in black holes.
- '*He does not play dice*,' is one of Einstein's most famous quotes, referring to God. He said it in response to Quantum Mechanics' implication that probability plays a key role in what Einstein preferred to believe was a deterministic universe. But his intuitive belief has been proven wrong.
- Einstein disputed the evidence for '**quantum entanglement**' in which two particles know about each other's change of state faster than the speed of light should allow[14]. He called it, '*Spooky action at a distance*.' (NB This proven phenomenon does not contravene the universal speed limit since *information* is not actually transmitted in the process.)

---

[14] Non-locality, defined on page 81, is the basis of 'quantum entanglement'. Two or more particles which form an interdependent system are 'entangled': a change of state of one particle results in the instantaneous change of state of the others. This entanglement remains even if the particles are very distant from each other.

With Regret

These last two errors of judgement disappointed Einstein's many friends in the physics community who held him in high regard.

Einstein had successfully challenged so many previously held theories and perceptions of reality. He was also a founding father of our quantum understanding of the world. And yet, he could not accept the challenge to perceived reality brought about by Quantum Mechanics, and continued his search for classical meaning in the new quantum equations.

> Many of us regard this as a tragedy, both for him, as he gropes his way in loneliness, and for us, who miss our leader and standard bearer.
>
> *Max Born, Nobel prize winning physicist*

Why Is Einstein So Famous?

Quantum Mechanics is arguably as important as Relativity (or at least, very nearly). However, no scientist is as singularly and firmly engraved on the public imagination in respect of Quantum Mechanics as Einstein is with Relativity. This was partly due to the fact that Quantum Mechanics evolved over a longer period of time and resulted from a far more collaborative body of work.

But of course Einstein's discovery that space and time were not absolute, proven by the 1919 demonstration of the bending of starlight, was of more than newsworthy interest, pulling the rug as it did from Mankind's sense of place in a hitherto absolute universe.

> The ideals of Aristotle and Euclid and Newton … the basis of all our present conceptions prove in fact not to correspond with … the fabric of the universe.
>
> *The Times of London, 1919*

The enormity of his discoveries propelled the single name Albert Einstein onto front pages everywhere, making 'Einstein' a household proxy for the word 'genius'.

War And Peace

While not closely involved in research related to nuclear energy, Einstein's pre-eminence and reputation was a door-opener to political leaders. That's why nuclear physicists, worried about possible Nazi development of a nuclear weapon, enlisted his assistance.

Having escaped Nazism and with certain knowledge of successful experiments in Berlin, Einstein shared their concerns and readily agreed to write to US President Roosevelt in 1939, thereby helping initiate the US's early research into such weapons.

But in the wake of the atomic bombings of Hiroshima and Nagasaki, and in the light of history, Einstein came to regret this letter. '*Had I known that the Germans would not succeed in developing an atomic bomb, I would have done nothing*,' he said.

Einstein himself was in actual fact a lifelong pacifist. This included his efforts after World War II to promote the international control of nuclear weapons.

The irony of Nazi bigotry

Ironically, the German failure to build a nuclear weapon was, in part, a product of the Nazi attack on the new physics of Relativity and Quantum Mechanics discussed earlier (see page 97). It led to an exodus of world-renowned physicists prior to World War II from Germany and from other European countries likely to fall under its influence. They left to find work (many having been barred from university posts in Germany), or out of principled objection, or fear; and in search of institutes working on the new physics rather than reviling it.

Their work in those pre-war years paved the way to the harnessing by Man of nuclear reactions. They broke with the academic tradition of collaboration and kept some of their scientific discoveries unpublished and unshared, thereby thwarting German nuclear weapon development.

Eventually, in the midst of war, some of these nuclear physicists converged in a remote region of New Mexico, together with thousands of others; part of a secret US project, nurse-maids to the very first nuclear weapons.

IMAGINE EINSTEIN'S EXCITEMENT

Einstein was a 26 year old German-born clerk in the Swiss Patent Office when he published his first paper on Relativity in 1905. This, together with his 1916 paper, amounted to a hugely significant advance in the search for a Theory of Everything: that magnetism, electricity, light, motion, matter, energy and gravity amongst other things are all manifestations of space-time in one form or another.

Probably, as he first tugged at a loose thread, exploring the nature of light, he had little idea the extent to which Newton's universe would unravel. Or that it would lead to a vastly different conception of the universe. Did he jump for joy or did he sit still with a sense of awe?

Of course, scientific advance is not achieved in such splendid isolation, or in just one evening with paper and pencil. Indeed some of Relativity's concepts were emerging before Einstein and some of its implications emerged later through the work of others. But, no doubt, Einstein experienced a version of this joy and awe.

'Something actually snapped'

Referring to the moment Einstein proved to himself that General Relativity explained the unusual orbit of Mercury, and hence that this theory over which he'd been toiling was correct, Einstein's biographer, Abram Pais, wrote, 'This discovery was, I believe, by far the strongest emotional experience in Einstein's scientific life, perhaps in all his life. Nature had spoken to him. Whilst the great man himself said, "*For a few days, I was beside myself with joyous excitement*."' Einstein himself told a friend later that he felt something in him had actually snapped.

From Subtle is the Lord: The Science and the Life of Albert Einstein

Imagine then how it must have felt to be so instrumental in all these discoveries. And for brief periods to be one of the few, if not the only person anywhere, who was properly aware of them.

Chapter

A LITTLE BIT OF MATHS (IF WANTED)

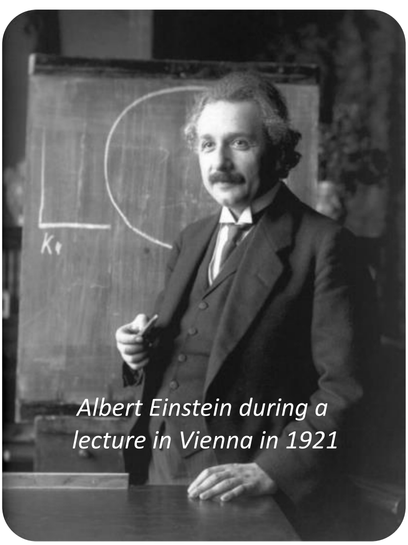
This chapter is a wholly optional read for non-serious mathematicians. In nine parts it presents a simplified version of the mathematical reasoning which lies behind Relativity theory.

Special Relativity

1 Space-time diagrams
2 Relative motion, Simultaneity and Causality
3 Solving the Twins Paradox
4 The Relativity Factor
5 Transformation between frames: of distance, time and speed
6 Space-time interval
7 The maths behind (apparently) increasing mass
8 Arriving at mass-energy equivalence, $E=mc^2$

General Relativity

9 Einstein's other famous equation: General Relativity



Albert Einstein during a lecture in Vienna in 1921

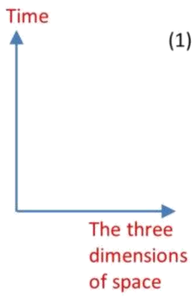
> The equations of general relativity are his best epitaph and memorial. They should last as long as the universe.
>
> *Professor Stephen Hawking, Physicist*

1 Space-time Diagrams

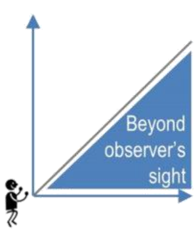
In 1908, mathematician Hermann Minkowski, building on Einstein's work, described space-time as a single entity, and developed space-time diagrams, a mathematical tool, to help solve problems in Relativity.

Minkowski expressed his idea as follows.

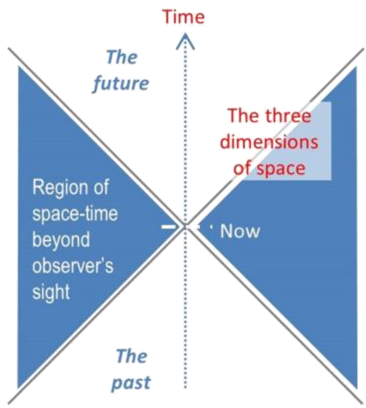
> Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.
>
> *Hermann Minkowski, Mathematician*



(1) A space-time diagram is like an ordinary graph of distance versus time, except that the distance axis now represents all three spatial dimensions



(2) We can draw a (grey) line to represent light-speed (since speed = distance / time). Events below this line are invisible to an observer as that would require travel faster than light. Events above the line are visible to the observer.



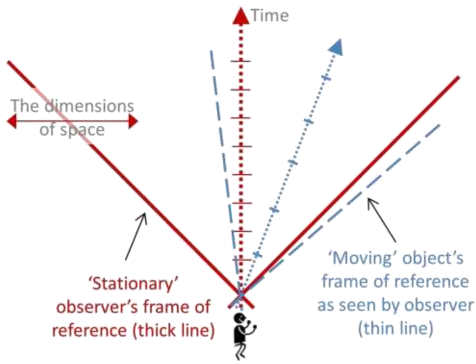
(3) We can extend the concepts at left to draw a cone for past & future. Inside the cone represents the universe's boundary of knowable space and time, both past and future.

Diagram (3) is called a space-time diagram. The dotted vertical line through the middle represents an observer's journey through space-time. Given that he believes himself stationary within his own bubble of reality, he travels only in time, but not side to side in space. This dotted line is called the observer's '**worldline**'.

2 Relative Motion, Simultaneity And Causality

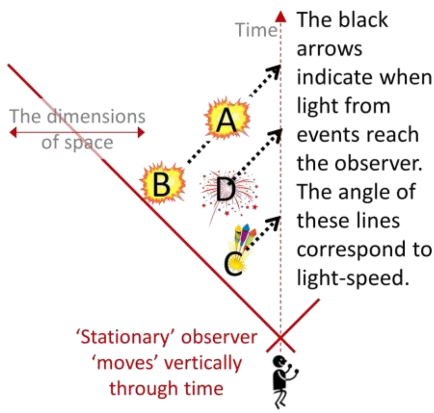
Relative motion

Using the space-time diagram tool let's look at the relative motion of **frames of reference** as discussed on page 46. In the space-time diagram at right, the 'stationary' observer observes the 'moving' object's reference frame. He sees it as rotated compared to his own, its time slowed and its distance contracted: shown here by the narrowing of the moving frame's dimensions of space.

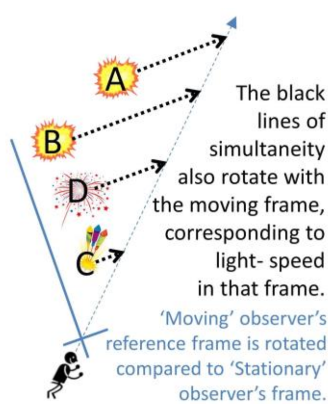


Simultaneity and Causality

The events A and B are observed to be simultaneous by the 'stationary' observer in the space-time diagram at right. This is because light from both A and B arrives at the same time, along the line of the black arrow. This line is known as a '**line of simultaneity**'. However, in the rotated reference frame of a moving observer (below right) the light from the same events, A and B, arrives at different times on his worldline.



In the case of event C (the lighting of fireworks) and event D (fireworks exploding), light from event C will always arrive at the observer before light from event D. In other words, 'cause' will always precede 'effect', no matter how fast one observer moves relative to the other. This is because moving reference frames can't rotate more than the angle for light-speed.

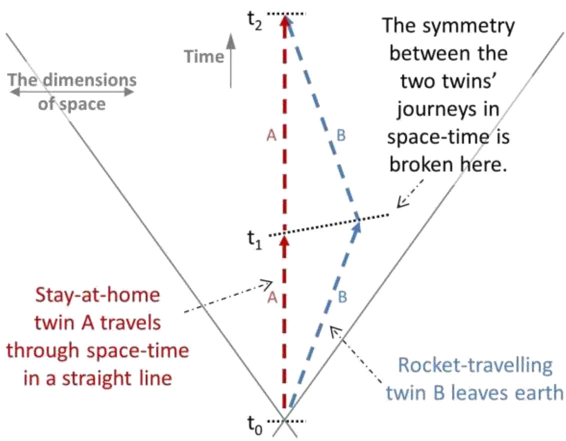


3 SOLVING THE TWINS PARADOX

We can understand the Twins Paradox using a space-time diagram. Let's consider what's happening to the twins. Recall from page 42 that one of the twins travels away from the other at high speed, let's say to planet Zog one million miles away. There she turns around and returns. The apparent paradox is that since each twin is moving relative to the other, then surely they both observe time slowing for the other twin. And so, when they reunite, each notices that the other has aged less than they!

Hidden inside the presentation of this simple and persausive paradox is an inherent, but incorrect, presumption: that the situation of each twin is identical, i.e perfectly symmetrical. But as the space-time diagram below highlights, the two situations are far from symmetrical.

From the outset, each twin is in their own bubble of reality, their frame of reference. Measurements they make are made with respect to their own 'coordinate system'. And, since, until $t_{1,}$ their relative motion is identical, so they observe identical length contraction and time dilation in the other twin's reference frame.



The diagram shows space-time from twin A's perspective. The story of the twins is symmetrical only until half way through twin B's journey. (A space-time diagram drawn from twin B's perspective would be a mirror image of this first half of the story, up until t1.)

However, at t_1 twin B changes direction to return to twin A. This break in her uniform motion breaks the symmetry of the twins' experiences. Twin B has swapped to another bubble: she's now in a different frame of reference; unlike twin A who remains in his. The next question is: how is that significant?

Given the symmetry up until t_1, we can assume that this plays no part in the overall scheme of things.

Twin A’s clock measures twin B’s total journey. This agrees with his calculation (since he knows the distance to Zog and twin B’s speed). However, he also observes slowing of twin B’s clock, and therefore that twin B ages less than he.

Twin B of course believes her clock is ticking normally. But, because of length contraction, the return distance from Zog is shorter and she covers it more quickly: that is, in less time than has registered on twin A’s clock. So she too observes that she has aged less than twin A. (This is exactly the same as the experience of the earth-bound muons in the Relativity proof on page 68.)

An identical conclusion is reached even if, instead, the space-time diagram is drawn from twin B’s perspective.

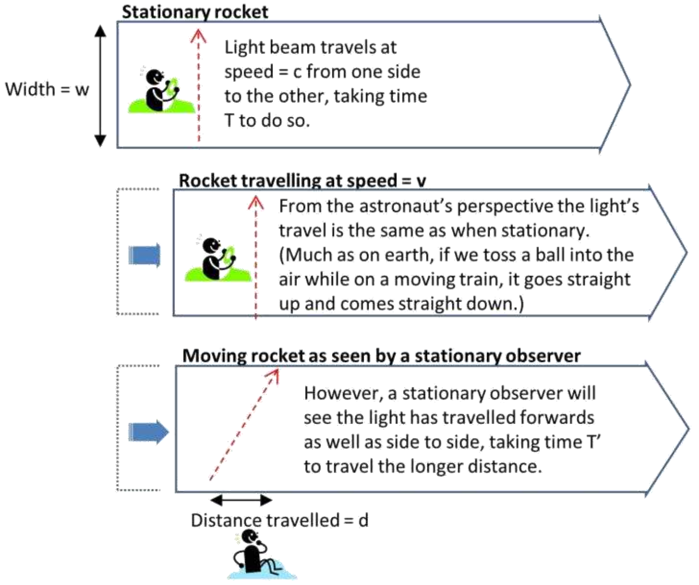
4 The Relativity Factor

(Also known as the Lorentz Factor)

Hendrik Lorentz was one of several physicists trying to make sense of the Michelson-Morley experimental result of 1887 which demonstrated the invariance of the speed of light, see page 29. And, before Einstein came along in 1905, they had arrived at a working mathematical description, albeit without having uncovered its physical interpretation. This mathematical description included two important components. Firstly the Relativity Factor, which gave the amount by which distance contracted and time slowed. And secondly, rules (i.e. equations) for **transformation between frames of reference** of distance, time, speed and momentum, when one frame is moving relative to the other - see Parts 5, 6 and 7 of this chapter.

Calculating the Relativity Factor

Consider the situation below in which a light beam takes time T to travel across a rocket of width w at the speed of light c. An astronaut in the rocket will observe the same thing, whether the rocket is moving or stationary. However, from the point of view of a stationary observer, the light must travel further, across a diagonal; and, given the invariance of the speed of light, will take longer to travel the greater distance, let's call that duration T'.



Now let's try to work out the relationship between T and T'.

From the astronaut's perspective, the distance travelled by the light is

$w = cT$ (1) (*from speed = distance divided by time*)

From the stationary observer's perspective, the distance travelled by the light is

cT'

But we know from Pythagoras' Theorem (describing the arithmetic relationship between the sides and diagonal of a right angle triangle) that

$(cT')^2 = w^2 + d^2$ (2)

And since we know the speed of the rocket, v, then we know that

$d = vT'$ (3)

So substituting equations (1) and (3) into equation (2) gives

$(cT')^2 = (cT)^2 + (vT')^2$

Dividing all three terms by c^2 gives

$T'^2 = T^2 + (v/c)^2 \times T'^2$

Rearranging

$T^2 = T'^2 - (v/c)^2 \times T'^2$

$= T'^2 \times [1 - (v/c)^2]$

So

$T^2 / T'^2 = [1 - (v/c)^2]$

So

$T / T' = \text{sqrt}[1 - (v/c)^2]$ (*NB sqrt = square root*)

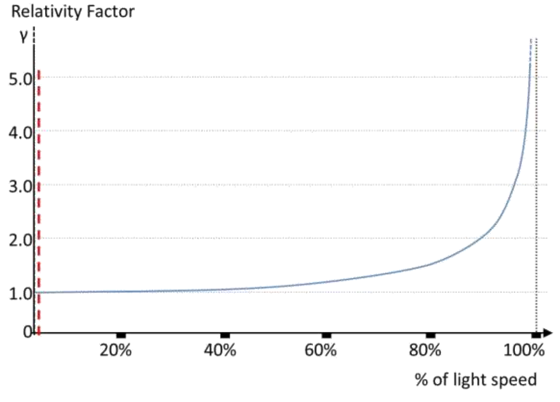
Now replacing the right hand side by a mathematical abbreviation**,** γ

$T / T' = 1/\gamma$ (where γ = Relativity Factor used to adjust T)

And so

$\gamma = 1 / \text{sqrt}[1 - (v/c)^2]$

In graphical form, this equation draws the curve below. As we've seen in earlier parts of the book, because distance and time are related through the invariance of c, the Relativity Factor is also used to calculate length contraction.

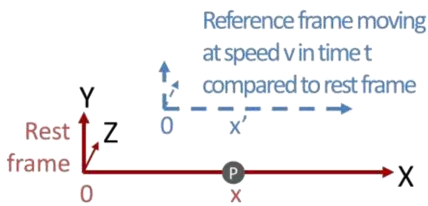


Our 'everyday speeds' are to the left of the dotted line.

5 TRANSFORMATION BETWEEN FRAMES: OF DISTANCE, TIME AND SPEED

Applying the Relativity Factor: Transformation of distance and time
We can use the Relativity Factor to calculate how distance and time change as viewed between two different frames of reference, one deemed to be stationary, the Solid-line frame below, and the other moving relative to it, the Dotted-line frame.

In the following example we will assume y = 0 and z = 0 to simplify the workings out



In the Solid rest frame the distance from the origin at 0 to the point P is x. In classical Newtonian physics to calculate the distance x' from 0 in the moving Dotted frame we would write

$$x' = x - vt \qquad (1)$$

In this equation vt is the distance the moving frame has travelled.

However, Relativity says that x and t have contracted and slowed by the Relativity Factor, γ. So substituting the equation for γ into (1) gives

$$x' = \frac{x - vt}{\mathrm{sqrt}\,[1 - (v/c)^2\,]} \qquad (2)$$

(Identical equations apply to y and z)

By analogy, we arrive at a similar equation for t'

$$t' = \frac{t - vx/c^2}{\mathrm{sqrt}\,[1 - (v/c)^2\,]} \qquad (3)$$

In this equation, the term vx/c^2 does a similar job as the term vt in equation (2), but needs further explanation

$$vx/c^2 = v/c \text{ times } x/c$$

where

x/c is a proxy measure of distance in the Solid frame of reference expressed in light-seconds (the distance travelled by light in one second)

v/c is a ratio which factors x/c according to the Dotted frame's speed.

Applying the Relativity Factor: Transformation of speed

On page 43 we discussed how the approach speed of two objects could never exceed light-speed, no matter how fast each object appeared to be moving relative to a third ‘stationary’ observer. The following describes the maths behind that.

Consider a rocket moving at speed $v_R = 0.6c$ relative to a ‘stationary’ observer A. Inside the rocket is an object moving in the same direction as the rocket at speed $u_R = 0.6c$ relative to the rocket. How fast does the stationary observer believe the object is moving? Let’s call that u_A.

Newtonian physics (which works just fine at relatively low speeds) would give the answer as the sum of the speeds

$$\mathbf{u_A = u_R + v_R = 0.6c + 0.6c = 1.2c}$$

But Relativity tells us that this is not possible, as it exceeds light-speed, c.

We arrive at the Relativistic equation by considering the different reference frames of the observer and the rocket and making the appropriate transformations to distance and time. So instead of presuming that

$\mathbf{u_A = x / t}$ (where x and t are distance and time in the rocket’s frame)

We recognise that

$\mathbf{u_A = x' / t'}$ (where x’ and t’ are distance and time in the observers’ frame)

By substituting equations (2) & (3) from earlier into this equation it is possible to arrive at

$$\mathbf{u_A = \frac{u_R + v_R}{1 + u_R v_R / c^2}}$$ (= 0.88c in our example above)

6 SPACE-TIME INTERVAL

The distance between two points in space

In 2D space, the distance, d, between two points is given by Pythagoras' Theorem.

$d^2 = x^2 + y^2$ (x, y are the lengths of the two sides of right-angle triangle)

In 3D space, Pythagoras still applies.

$d^2 = x^2 + y^2 + z^2$ (x, y, z, as in the 2D case, are the distances between the two points in each spatial dimension)[15]

In the 3D geometry of classical physics, if Newton observes a distance, d, in his frame of reference he can expect the same distance, d, will be measured by anyone else, moving relative to his own frame of reference. We say that d is '**invariant**'. And this remains true, irrespective of the relative size of x^2 (bigger, smaller or equal) to y^2 or z^2, since they are all spatial dimensions.

The distance between two events in space-time

It's tempting to extend this logic again to add a fourth dimension of time, but we can't. While space and time are more similar than we perceive, they're not the same. We can't presume to extend Pythagoras to 4D space-time. 3D geometry doesn't work the same here - why should it?

As we saw on page 46, in space-time we don't talk about 'points' (i.e. 'where': x, y, x), we talk about 'events' (i.e. 'where' and 'when': x, y, z, t).

We measure the dimensions of space, x, y, z, in metres, and the dimension of time, t, in seconds. To combine 'distance in time' in the same equation as 'distance in space', we must somehow convert time to a proxy measure in metres. Since the speed of light, c, is constant, i.e. invariant across all frames of reference, it is safe to calculate this proxy measure as follows

'Distance in time' = ct (i.e. **c** *in metres/sec* **times t** *in secs* **= ct** *in metres*)

Furthermore, the word 'distance' loses meaning when applied to the time dimension. Instead, physicists talk about the '**space-time interval**' or 'interval'. This conveys the idea of 'distance in space' and/or 'distance in time'. It is denoted by s^2, not s, for reasons we'll come to.

Imagine two events separated in space by a distance, d, where $d^2 = x^2+y^2+z^2$. The two events occur at different times, the difference in time being t (i.e. ct once converted to our proxy quantity). We can presume that the space-time interval s^2, is a function of distance in space d^2, and distance in time $(ct)^2$. As with our 3D case, let's see what happens as the relative sizes of d^2 and $(ct)^2$ vary to each other.

---

[15] Strictly speaking x, y, z should be written as Δx, Δy, Δz: the 'delta' (or difference) between two points. On these pages we take that as understood, for simplicity.

$d^2 > (ct)^2$ The two events are separated by more space than time. Nothing travels fast enough for event 1 to cause event 2: the interval is '**spacelike**'.
$d^2 < (ct)^2$ The two events are separated by more time than space. A signal can travel fast enough for event 1 to cause event 2: the interval is '**timelike**'.
$d^2 = (ct)^2$ Light starting its journey simultaneously with event #1 would arrive at event #2 precisely where and when it occurs: the interval is '**lightlike**'.
These three cases correspond to areas of the space-time diagram in Part 1: the shaded and white regions, and the grey line of the light cone's outline respectively.

This demonstrates that, unlike our 3D case, the relationship between d^2 and $(ct)^2$ matters. The third equation, $d^2 = (ct)^2$, provides the clue to understanding that relationship. For objects travelling at the speed of light distance has contracted to nothing and time has slowed to a standstill. The space-time interval between two events in this case is 0. We can rearrange the third equation to give this result. If

$$\mathbf{d^2 = (ct)^2}$$

So

$$\mathbf{d^2 - (ct)^2 = 0 = s^2}$$

Or, as more normally written in expanded form for d^2

$$\mathbf{s^2 = x^2 + y^2 + z^2 - (ct)^2}$$

In this form, we can see why the space-time interval is denoted by s^2 and not s. The right hand side of the equation could result in a negative value. (Physicists prefer to avoid unnecessarily having to take the squre root of a negative number.)

Invariance in space-time

In our 3D Newtonian example, we saw that distance is invariant. It remains unchanged no matter the relative motion of any observer.

However, at high relativistic speeds, distance is not invariant. Differently moving observers will observe different lengths. And we know that likewise time is not invariant. However, in 4D space-time, we find that the space-time interval is invariant, i.e. the interval between two events as seen from the reference frames of two differently moving observers are equal. So that

$$\mathbf{s^2 = s'^2} \qquad \text{(where the symbol ' denotes the second observer)}$$

So, using our equation for s^2 above, can say that

$$\mathbf{x^2 + y^2 + z^2 - (ct)^2 = x'^2 + y'^2 + z'^2 - (ct')^2} \qquad (1)$$

The equations defining the relationships between x & x', y & y', z & z', and t & t' were established in Part 5 (equations (2) and (3)). By substituting these equations for x' and t' into (1) above leads to the result

$$\mathbf{x^2 - (ct)^2 = x^2 - (ct)^2} \qquad \text{(assumes y = 0 and z = 0 to simplify calculations)}$$

So proving that space-time intervals are invariant in the 4D geometry of space-time, in the same way that distance is invariant in the 3D geometry of space.

7 The Maths Behind (Apparently) Increasing Mass

We described on pages 21 and 48 how an object's mass *appears* to increase as its speed increases, but in fact remains unchanged. And we described that it is actually the object's **momentum** which increases.

Momentum is the amount of motion of a moving body. It is a measure of the tendency of a moving object to continue moving. For instance, the heavier our object or the faster its speed, the more momentum it has: a fast-moving truck is harder to stop than a slow-moving bicycle.

So, in the form of an equation, momentum is a function of mass and speed

$\rho = mv$ (ρ (Greek letter: rho) = momentum, m = mass, and v = speed)

$\rho = m\frac{dx}{dt}$ (where v = dx/dt = difference in distance / difference in time assuming no movement in y & z dimensions)

This is the classical physics equation for momentum. Relativistically, observers in different frames will measure time differently, and we must transform the measurement of time between frames accordingly.

Suppose that t' is the time as measured in the object's frame of reference. So,

$$\rho = m\frac{dx}{dt'}$$

If t = time measured by an observer, then this could be rewritten as

$\rho = m\frac{dx}{dt}\frac{dt}{dt'}$ but from time dilation we know that dt/dt' = y, so

$\rho = ymv$ = momentum as measured from observers reference frame.

Misleading names

On page 48 we also said that physicists had helped create a false impression that mass increased in an attempt to help explain what was going on. They even gave the name '**relativistic mass'** to this apparently increased mass, to differentiate it from what is still referred to as the object's '**rest mass**'.

The term relativistic mass is less used nowadays. Einstein himself was not impressed with this approach from the outset.

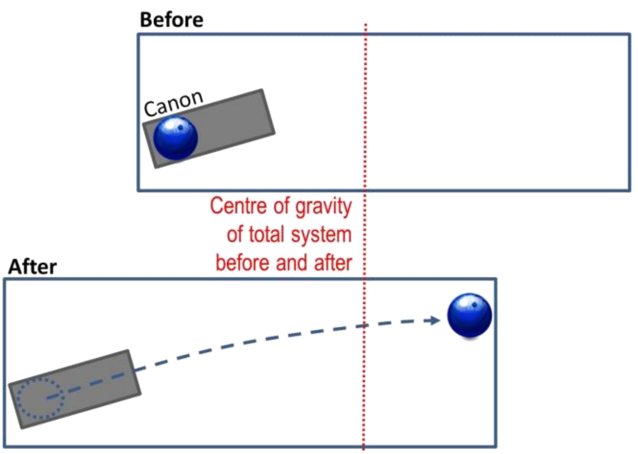
> *'It is not good to introduce the concept of the [relativistic] mass of a moving body for which no clear definition can be given. It is better to introduce no other mass concept than the 'rest mass' … [and] instead … to mention the expression for the momentum and energy of a body in motion.'*

8 ARRIVING AT MASS-ENERGY EQUIVALENCE, $E=mc^2$

This most famous of Einstein's equations highlights the enormous amount of energy locked up in matter. We saw on page 49 how physicists had observed an apparent relationship between mass and energy. This is how Einstein expressed the idea in his second 1905 paper on Relativity.[16]

> We know that, '*If a body gives off … energy … in the form of radiation, its mass diminishes … [and] … becomes energy of radiation …, so that we are led to the more general conclusion that … the mass of a body is a measure of its energy-content …*'.

Einstein used the following thought experiment to examine the relationship between mass and energy. Imagine a canon secured to one side of a very strong box, itself resting on a frictionless surface.



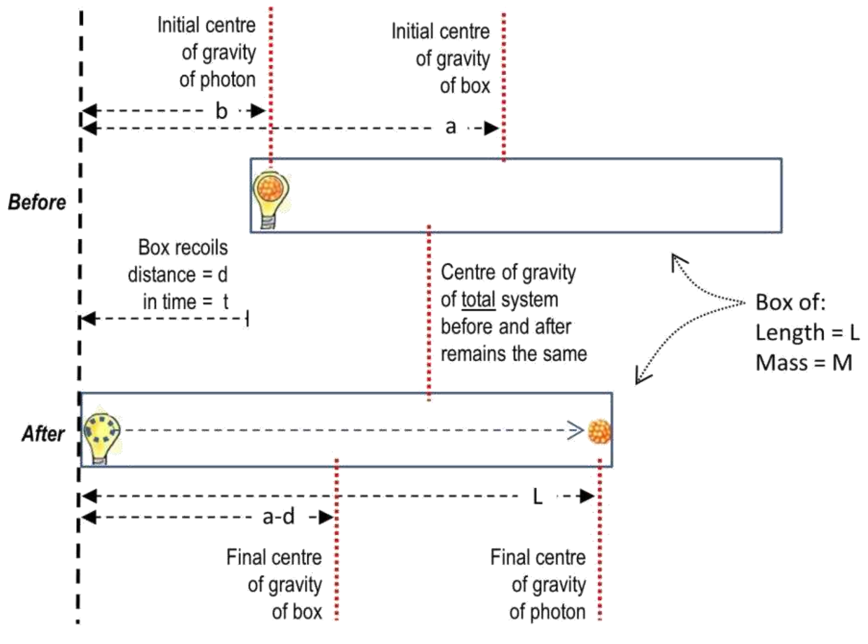
The canon's recoil has moved the box to the left. The weight of the cannonball has moved to the right. Therefore the centre of gravity of the total system remains in exactly the same place in space, and momentum has been conserved.

The canon is fired. As the cannonball leaves the canon travelling left to right, the recoil makes the canon and the box to which it is secured move in the opposite direction. When the cannonball hits the opposite wall it obeys the Laws of Conservation of Energy and transfers its momentum

[16] This very short paper was titled, 'Does the Inertia of a Body Depend Upon Its Energy Content?'

energy to the box. As a result the box stops moving, coming to rest to the left of where it started. The centre of gravity of the whole system (canon, cannonball and box) however is the same, because the cannonball is now on the right hand side of the box and not on the left where it started.

Einstein's actual thought experiment swapped a light source for a canon, a particle of light for the cannonball and floated the box freely in space. The light source converts electrical energy into a photon with a momentum able to move the box; i.e. as if it actually had mass. So it seems logical to conclude that there must be some equivalence between the energy of the travelling photon and the impression of mass, as evidenced by its box-stopping momentum.



The light particle's recoil moves the previously stationary box to the left. The momentum of the light particle then brings the box to a halt when it strikes the opposite wall. The centre of gravity of the system remains the same.

Using well established Newtonian concepts, there are a number of things we know about the total system above.

Firstly, the time taken for the photon to travel across the box (at the speed of light c) is

t = L/c (1)

Secondly, the Law of Conservation of Momentum tells us that momentum is conserved as it is transferred from photon to box. So

(momentum of photon of light) = (momentum of moving box)

One of Maxwell's equations for electromagnetic waves gives us the left side (E/c), and one of Newton's the right (mass times speed). So

E/c = M times (speed of box) (*where E is the energy of the photon*)

So

E/c = Md/t (2)

Substituting (1) into (2)

E/c = Md/(L/c)

Rearranging

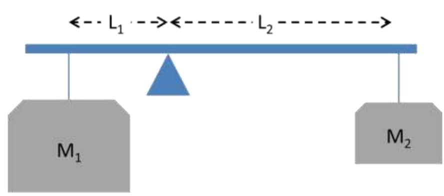
$E = M(d/L)c^2$ (3)

Thirdly, by analogy with the canon and cannonball in a box, the centre of gravity of the system before and after must stay in the same place since no forces or masses external to the box have influenced the system. Now let's give the photon a mass equivalence of m.[17] So

(centre of gravity before) = (centre of gravity after)

(Ma) + (mb) = M(a - d) + (mL)

(This is analogous to calculating 'moments' in a balanced system as in the graphic at right.)



For a see-saw balanced around the fulcrum the following applies: $M_1 \times L_1 = M_2 \times L_2$

Finally, substituting (4) into (3) gives

$E = M(m/M)\,c^2$

Simplifying

$E = mc^2$

---

[17] This was Einstein's brilliant insight. To substitute a term for mass equivalence into the equation derived from the Law of Conservation of Momentum.

You might wish to suggest that an electromagnetic photon of energy E would in any case be expected to have mass equivalence and then ask, but what has that to do with *real* matter? At this point, it's worth remembering the following quote from Einstein, discussing real matter. We know that, 'If a body gives off … energy … in the form of radiation, its mass diminishes … [and] … becomes energy of radiation …, so that we are led to the more general conclusion that … the mass of a body is a measure of its energy-content …'

Calculating the mass-energy equivalence of a 100kg England male rugby player

Speed of light 300,000,000 metres per second.
Therefore $E=mc^2$ means
1 kg of matter = 90,000 million million Joules of energy.

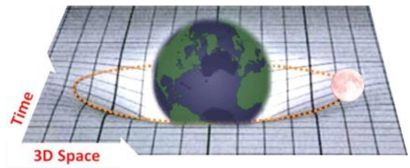
In 2012/3, the UK used 215 million tonnes of oil equivalent *
= 9,000,000 million million Joules of energy

Therefore a 100 kg male rugby player would service the total UK energy for a year if completely converted to energy through a nuclear reaction.

* Source: www.gov.uk

9 EINSTEIN'S OTHER FAMOUS EQUATION: GENERAL RELATIVITY[18]

As far as the general population is concerned, Einstein's most famous equation is $E=mc^2$. But for physicists his most important equation is the one which John Wheeler is describing in words at right: the equation of General Relativity (GR). It's this equation which Professor Stephen Hawking is talking about in his quote on page 107. (Strictly speaking the equation is a set of equations.)



> Matter tells space-time how to curve and curved space-time tells matter how to move.
>
> *John Wheeler*

The maths behind this equation is very complex. But here we'll try to shed just a little light on its structure.

The equation describes what's happening in the visualisation above. (To be precise, in the reality depicted in the *imperfect* visualisation above; as we've seen, 2D visualisations of 4D space-time are inherently flawed.) Let's tease apart what's happening in this visualisation.

1. An object with mass …
2. is placed in 4D space-time causing it to curve …
3. and this curvature in turn acts on this and other objects.
4. And all this takes place in a universe defined by constants.

1 Energy-density

We've seen that matter is very densely packed energy. Physicists tend to talk about 'energy-density' when referring either to lower density energy forms, such as a photon, or much higher density forms such as matter. The most dense of all are 'black holes'; so dense that nothing can escape their gravitational pull, not even light.

So while in Newton's equations we see 'mass' (m) appearing in his equations of motion, in Einstein's equation of GR we will see a term describing the energy-density of objects.

---

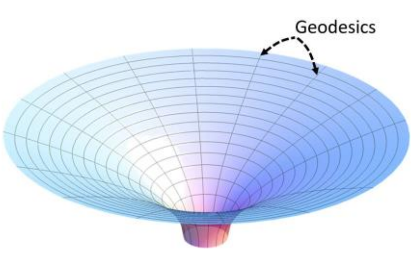
[18] Einstein's work on General Relativity actually comprised many papers over a 10 year period, culminating with the publication of 'General Theory of Relativity' in 1916.

2 Four-dimensional space-time is curved by an energy-density

While physicists don't know what space-time is, its effects can be modelled. They consider it to act a bit like a uniformly smooth fluid. When an energy-density is introduced into this fluid it pushes some fluid aside. In so doing it is causing a local area of higher pressure or 'stress' in the fluid around the object. This higher pressure in turn pushes back creating a pressure on the object. The pressure gradients in the space-time fluid (physicists refer to it as the 'space-time field') are like gradients in a landscape of hills and valleys. And just like walkers in a landscape of hills and valleys, objects prefer to take the least energetic path through the landscape. It follows, from item 1 above, that it is energy-density that curves space-time; and the greater that energy-density, the greater the curvature. (Because the GR equation relates to the space-time field, it is often called **Einstein's Field Equation**.)

Two important components of Einstein's GR equation flow from here. Firstly, the equation needs to include the concept of pressure or stress in the space-time field. Secondly, it needs to describe this landscape in terms of *space-time's geometry*. This is a 4D version of the geometry we learnt at school.

For example, consider a '**geodesic**'. This is a mathematical term which will also be familiar to geographers. It is the shortest possible line that can be drawn between two points on a curved surface. An example of a 3D geodesic on Earth would be an aircraft flying the shortest route between London and New York. It will not fly horizontally across the North Atlantic, as a 2D map might suggest, but follow a curve which skirts south of Greenland, and then flies down the east coast of Canada. This is actually the shortest distance between London and New York on the near-spherical Earth.



This 3D representation of 4D space-time shows that it has been stressed (caused to curve) by a high-energy-density at the base of the funnel. A subset of the resulting geodesics are drawn on the surface of the curved surface. Some of these funnel down to its centre, from a start point on the rim to the end point at the high-energy-density. And some orbit the central energy-density.

3 How the curvature of space-time affects the behaviour of objects

An object floating freely in space-time and with no external forces acting on it will do just that: continue floating in space-time. But, if there is another, more massive, object nearby causing space-time to curve in its vicinity, then the smaller object will be influenced to travel a geodesic path toward the larger object.

It should seem obvious that the degree to which it is encouraged to travel along a particular geodesic will depend on a few factors. These include the relative masses (i.e. energy-densities) of the two objects, the distance between them, and the relative speed between the two objects.

Depending on these factors, the objects will do one of three things.

- Be drawn only a little toward each other, deflecting each very slightly from its original course.
- Be captured into orbit: either one orbiting the other, or possibly, orbiting each other if they are of similar mass. In either case, each object's initial speed is just strong enough to keep it from falling into the other, and just weak enough to be unable to escape being captured into orbit.
- Fall toward each other and eventually collide.

All of these could be described as the ultimate freefall, since in all cases the objects will feel as weightless as a freefall parachutist (until of course the object collides with something else).

4 A universe defined by constants

We have learned already about the important role that the speed of light 'c' plays in the design of the universe. So it is not a surprise to find it in Einstein's equation of GR.

From school maths you may remember the important role that the mathematical constant π (pi) takes in any geometry involving curves. It is used when calculating for instance the circumference or area of a circle; or the surface area or volume of a sphere. So it's perhaps not a surprise, given the *curvature* of space-time, that we will see it pop up also in Einstein's equation of GR.

The next constant we find in his equation is the **gravitational constant**, 'G'. This 'big G', as it is sometimes called, is the same as the big G in Newton's equations. The role played by this physical constant is simply to scale the answer that pops out of mathematical equations and thereby ensure they agree numerically with measured results.

Finally, there is the **cosmological constant** denoted by the Greek capital letter lambda (Λ). This is the constant which Einstein introduced to make his equation describe a non-expanding/non-contracting universe. Once it was confirmed that the universe was in fact expanding, he set Λ to zero. More recently, Λ is finding a new lease of life helping understand how dark energy influences the universe's expansion.

Einstein's equation of General Relativity
When Einstein put the above together, he arrived at his equation of General Relativity.

$$R_{\mu\nu} - \frac{Rg_{\mu\nu}}{2} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

The left hand side of the equation deals with space-time geometry and the right side with the properties of an object with energy-density. The various terms are explained below.

Before looking at the main terms, we should say a few words about the subscript characters, 'μ' (Greek letter 'mu') and 'ν' (Greek letter 'nu').
Since space-time has four dimensions so the relationship between objects and space-time will have a component in each dimension. (If you recall your school physics, this is similar to 'vectors' which have components in several dimensions.) Here μ and ν each represent the four dimensions of space-time. They therefore each have four values, conventionally: 0 for time and 1, 2, 3 for space. So what the subscript says is: don't forget to add together the components across all of the dimensions.

But why are there two subscript letters and not just one? Because there is a complex interplay between the object and space-time as per John Wheeler's quote. So the effect of the object on space-time has to be calculated at the same time as the effect of space-time on the object.

It is for this reason that the equation of GR is more properly described as a set of 10 equations. Since each of the ***2*** letters, μ and ν, can take ***4*** values, so there are 2 to the power 4 possible combinations of values, i.e. 16. However, 6 of these are mathematically equivalent to others (e.g. $\mu=1$ and $\nu=2$ is equivalent to $\mu=2$ and $\nu=1$) so that leaves 10 unique equations in the set.

The terms '$R_{\mu\nu}$' and 'R' are mathematical terms used to describe 4D geometry.
In the case of Relativity that means the shape of space-time and the extent of its curvature in response to the presence of an energy-density such as matter.

The term '$g_{\mu\nu}$' captures the causal structure of space-time.
It describes which events in space-time can influence which other events. As such, it comprises notions such as time, distance, volume, curvature, angle and separating the future and the past.

The term '$T_{\mu\nu}$' describes the properties of our object with energy-density.
This includes its energy-density, a representation of its momentum, and a representation of the pressure (or stress) between it and space-time's curvature.

Einstein and Newton

At low speeds, Einstein's equation of GR reduces to Newton's famous Law of Universal Gravitation.

$$F = \frac{G\, m_1 m_2}{r^2}$$

In this equation, the force of attraction, F, between two objects is a function of their masses, m_1 and m_2, the Gravitational Constant 'Big G', and the square of their distance, r, from each other. (Exactly how Einstein's equation reduces to Newton's equation is beyond the scope of this book.)

ACKNOWLEDGEMENTS

I did not set out to write a book, only to understand Relativity. It was not the first time. There had been many failed attempts. The idea ‘that the universe was not as it seemed’ compelled perseverance. Thanks to generous inhabitants of the internet there are several good explanations of Relativity which, while still fairly technical, were partially comprehensible even to me. These and other sources are listed at the end of this book and I am indebted to them all.

Finally, early in 2013, with progress being made I began to write notes, lest I forget! So this book was born. My first draft, perhaps unsurprisingly, had significant errors. The late Dr Rodney Hillier, Bristol University Astrophysics Department Emeritus, was patiently generous with his time in explaining where these were. This was typical of a man who, even after retirement, gave readily to the public advancement of science.

A number of family and friends, many of whom are not of scientific bent let alone shown any previous interest in Relativity, read later drafts and picked me up whenever I succumbed to not writing simply or clearly. So thanks to Henri, Jo, Katharine and David Hulman, to John Gordon and Tom Sheppey. And, especial thanks to my wife Sarah, who, despite possibly being the least interested initially, read two drafts and challenged my explanations repeatedly and very helpfully. (I’m sorry you ended up dreaming about Relativity.)

Finally, I am particularly grateful to Professor Elias Brinks of the Centre for Astrophysics Research at the University of Hertfordshire. He responded to my unsolicited request for help to check the manuscript. Despite a high research and teaching load, he reviewed the final drafts and helped me understand and correct the more nuanced aspects of Relativity. He also recruited others to review the draft, all of whom provided helpful comments: Jake Dungworth, James Hanson, Rod Martin and Lewis Palmer. My sincere thanks to all these also. From the outset, Professor Brinks kept faith with the

book's intended simplicity, guiding me through final corrections with a style of teaching I imagine his students must appreciate greatly.

Final responsibility cannot, of course, be avoided. Any remaining faults are mine and mine alone.

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Main revisions from October 2016:

- The chapter, *Relativity Over a Cup of Coffee* has been significantly revised.
- The pages 41, 43, 44 and 46 in the chapter *More Detailed Logic* have been significantly revised.
- There are additions to the chapter *A Little Bit of Maths*: Parts 2, 5 and 6.

NB. Professor Brinks reviewed the first edition of *Relativity Explained* and the new pages 44 and 46.

Revisions January 2019

Main revisions from April 2018:

- The positioning within the text of the sections on '*apparently* increasing mass' in both *Relativity Over a Cup of Coffee* and *More Detailed Logic*.
- The maths used in Part 7 of the chapter *A Little Bit of Maths*.

NB. Professor Brinks reviewed the source material used in Part 7 of the chapter *A Little Bit of Maths*.

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