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Introduction

TIME ACCORDING TO PHYSICS

IT IS REMARKABLE THAT after millennia of debate and study, we still find the concept of time difficult to pin down. And while we have come a long way in addressing how time fits into our fundamental physical theories of the universe, it remains one of the deepest and most intriguing questions in all of science. Many of those working in the foundations of physics today regard the nature of time as the greatest remaining scientific mystery. Of course, one can easily list other outstanding scientific problems that some would argue compete with it in terms of importance, like the nature of consciousness, the origin of life, the origin of the universe, and so on, but there is something about this thing we call time that makes it enduringly fascinating.

One reason for the difficulty in understanding the nature of time is that, unlike other fundamental concepts, such as space and energy or the structure of matter, it is incredibly hard to be *objective* about it. This is in part because we are imbedded and trapped within time in a way that is tricksier than the fact that we also exist within space. What we can say about time is therefore unavoidably coloured by our perceptions. After all, while we can think of many familiar concepts that exist outside of time, such as truth, justice, or even the laws of nature themselves, we cannot escape the fact that our reality is governed by passing time and by change. What could be more natural than the sense that time flows smoothly from one moment to the next? Existence, it seems

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to us, is not like an old movie reel, made up of discrete frames, but is smooth and continuous. It also seems obvious to us that time is irreversible: that the past comes before the future and not the other way round. After all, how could it be otherwise?

Oh, if only it were all that straightforward. One of the many lessons we have learned from modern science is that we cannot always trust our intuition. The American philosopher Craig Callender refers to those features of time that we perceive or experience subjectively—such as time flowing, its direction, that the present moment is special, and that the past is different from the future—as *manifest time*,[1] and he distinguishes it from the various ways time enters into the laws and equations of physics, collectively called *physical time*. I like this distinction, and throughout this book I will be using these two terms. Indeed, the challenge of reconciling them will be its central theme.

Most physicists and philosophers today not only acknowledge that there is a complete disconnect between manifest time and physical time, but that manifest time gets us nowhere in trying to understand the true nature of reality. You might wish to argue that *all we can ever say* about said nature of reality is based on how we perceive it—that, like it or not, epistemology (what we can know about the world) always trumps ontology (how the world is), a distinction that applies to time more so than to other concepts, which we can at least try to view objectively. But manifest time is vaguer that that. As Callender himself has remarked, 'Manifest time is not a reflection of time as we directly experience it. It is informed by experience, to be sure, but it is instead time as it arises from a kind of regimented common-sense picture of the world.'[2] We know in physics that 'common sense' isn't always the best tool to employ when trying to understand the world. Indeed, many would argue that the whole enterprise of reconciling manifest time and physical time is a complete, as it were, waste of time. I will be exploring whether this is indeed the case.

But I am a physicist, not a psychologist, so I always endeavour to explain the external world in a way that holds true even if I did not exist. Of course, I know that in doing so I am still having to construct models of reality inside my brain. I also reluctantly admit that I often hear

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Einstein's famous quote ringing in my head: 'The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction. There is no logical path to these laws; only intuition, resting on sympathetic understanding of experience, can reach them.'[3] However, I believe with every fibre of my being that it is the job of physicists to try as best they can to differentiate between external, objective reality and how we perceive and experience it.* When it comes to the stark difference between physical time and manifest time, this challenge is even greater, for our intuition, which Einstein insisted was vital, can be very deceptive.

And yet manifest time is so deeply intrenched in our psyche that maybe we should not be too hasty in dismissing it. Maybe we should try a little harder. After all, as we will see, physical time has some very serious problems of its own. To quote Callender again: 'By dismissing [manifest time] as illusory, one removes the project of explaining [it] and places it on the desks of psychologists. The psychologists, however, don't know it's on their desk.'[4] The physicist Lee Smolin also makes what is in my view an excellent point: 'Logic and mathematics capture aspects of nature, but never the whole of nature. There are aspects of the real universe that will never be representable in mathematics. One of them is that in the real world it is always some particular moment.'[5] So, rather than trying to make sense of manifest time starting from our best theories of physical time—as you might expect a decent physicist or philosopher to do—maybe there are aspects of manifest time that can guide us to a better and more unified picture of physical time, and get us closer then to its true nature.

There are a number of features of our physical reality that have been studied deeply and are well understood by science, such as the laws of mechanics, the nature of light, the constituents of atoms and the forces that hold them together, the life cycle of stars and the large-scale

* As a quantum physicist, I nevertheless believe that there is an objective reality out there independently of what we call a quantum measurement. This is an issue that we quantum physicists argue about and regarding which we have come up with various theories and interpretations. But this is not a book about quantum mechanics (although the subject will play a big role in our story of time later on).

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structure of our galaxy. But these are all aspects of our universe that we are able to detach ourselves from in order to examine and study them objectively. . . . Not so time. Maybe it is even a mistake to try to understand the nature of time without taking our subjective experience into account. After all, unlike designing an experiment to study some property of matter or gather data from observations of the world around us, we cannot study time from the outside. To understand time means, by definition, to express the way we experience it.

But are we able to say more? Can we gain a better understanding of the reality of time independently of our perceptions?

Before I wade into the physics and our modern scientific understanding (or misunderstanding) of the meaning, nature, and role of time, let me first address a few less technical aspects that you don't need a physics background to think about.

Could Time Be an Illusion?

You might consider time to be such a fundamental feature of our existence that there really is nothing profound or meaningful that we *can* say about it. Maybe time, like space, simply is. Many have even argued time out of existence altogether. For example, if we were to split it up into three components: the past, the present and the future, then we can examine each in turn. Those who deny the reality of time will say something like this: The past has happened and is gone; all we have left of it is the *record* of past events (in our memories, or in books, photographs, or on film), all of which can only ever form a part of the present moment (when we access those records). But the events themselves *no longer exist*. In contrast, all there is of the future is our predictions, hopes, and beliefs about what might happen, which are again states of our minds in the present. Regardless of whether the future is predetermined or not, it has *yet to exist*.

That leaves the present moment itself; surely 'now' is real. But although we 'feel' that our now is a solid, changing moment steadily sweeping through time, converting the future into the past, it is nonetheless just an instant and as such does not have any duration. The physical definition of 'now' is not a minute long or a second long, the

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time deniers will argue; it is the edge of the shadow between light and dark, between what is to happen and what has happened. It has no thickness. The constantly changing present moment is no more than a dividing line between past and future and so does not have a tangible existence of its own.

Thus, if none of the three components of time exist, then there is nothing left, leaving the whole of time as illusory! Many thinkers going back two and half thousand years have argued thus.

If this all sounds like a clever sleight-of-hand, don't worry: A number of philosophers of time, and physicists for that matter, subscribe to a diametrically opposite view, known as 'eternalism'. This holds that all three components—past, present and future—are equally real! This idea, which we will examine more closely later on, emerges from an idea called the block universe, which gained prominence after Einstein put forward his first theory of relativity, in which time is regarded as the fourth dimension of spacetime. In this picture all moments in time co-exist in the same way that all points in space exist. Einstein famously stated that 'the distinction between past, present and future is only a stubbornly persistent illusion'.[6]

If you don't fancy either of these radical views: that time doesn't exist at all or that all times exist, then there is a halfway house known as philosophical 'presentism', which holds that while the past and future do not exist (one has happened and gone, and the other is yet to happen) the present moment is nevertheless real. A related idea is the 'growing block universe' view, in which the past and the present exist while the future does not, but instead gradually comes into being.

So, you see all options are available on the menu. But which of them is the correct one?

In fact, just to make sure you are fully aware of the scale of the problem and level of disagreement among people who have thought long and hard about the nature of time, it might even be the case that time is what is called an 'emergent property' of reality, a bit like the concept of temperature, that only makes sense in our everyday world of experience, but becomes meaningless when we zoom in on the fundamental concepts that underpin reality.

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The earliest arguments for the non-existence of time go back to the pre-Socratic Greek philosopher, Parmenides of Elea, in southwest Italy, who flourished in the fifth century BCE. Only fragments of his work survive, including his greatest work: a poem called *On Nature*, in which he describes two views of reality. The view of interest here is the first one, called *The Way of Truth*, in which he denies the reality of change, arguing that change is impossible and that its very notion is incoherent; rather that everything which exists is permanent and unchanging.[7] Parmenides was no fool and presumably could clearly see change all around him, but like many of the ancient Greek thinkers he had talked himself down the rabbit hole of deductive logic from which it was hard to escape. He was certainly persuasive enough that his more famous student, Zeno, whom we will meet shortly, also held that continuous change, or a 'flow' of time, is just an illusion.

Another Greek philosopher worth mentioning is Heraclitus, who was born around 500 BCE in the city of Ephesus, now in modern Turkey. Little is known about his life, but what we do know paints him as a complex character and, as far as we can tell, a rather miserable one to boot. His philosophical ideas were, like him, paradoxical and cryptic to the extent that he earned the epithets 'The Philosopher of Riddles' and 'Heraclitus the Obscure'. Of interest here, however, is that his view of time stands in stark contrast to that of Parmenides. For Heraclitus was obsessed with change and viewed the world as being constantly in flux, always 'becoming' but never 'being'. The popular notion of a river of time, flowing past us, can be traced back to him.[8]

That is not the only way philosophers throughout history have thought about flowing time. For instance, rather than thinking of time flowing past us as we stand on the riverbank, we can imagine that we are in a boat carried along by this river watching the world unfold. In fact, in this poetic example we would need to be facing away from the direction of travel, with our backs to the future, watching the past recede away from us, but never seeing what is coming up.

Two thousand years later, Isaac Newton argued that time provides the backdrop for all change. And because he believed that time is absolute and external, he argued that it continues to exist and flow even

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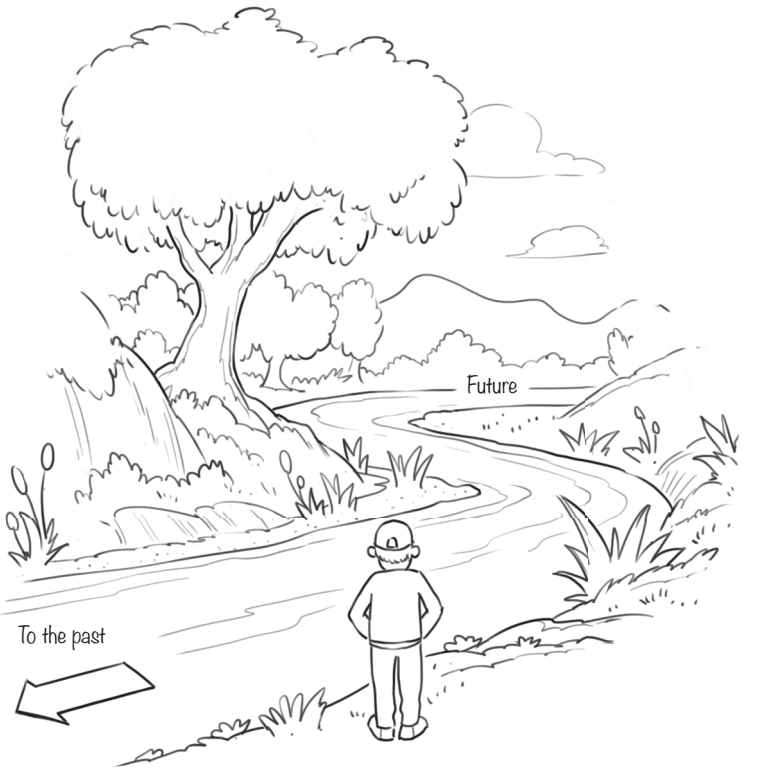

FIGURE 1. Does the river of time flow past us as we stand on its banks? If so, then you might think it should flow from the past to the future, but in fact it would be the other way around: from the future to the past, since time upstream has yet to happen, and as it flows past us it flows downstream to become the past.

when there is no change. But it seems we still need time if we are to measure change. However, while time may not require change in order to exist, what about the other way round: Does change require time? Well, one can easily think of examples involving things that change, but which are not necessarily changing *over time*. Atmospheric pressure changes when you climb to higher altitudes, the speed of a car changes when you press your foot on the accelerator pedal, the clarity of an image under a microscope changes when you use different lenses or alter their focus, and my mood changes when my football team wins or loses a match. However, in physics when we talk about changes over

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FIGURE 2. Or do we float along the river of time watching events unfold on the riverbanks? Now the direction of flow really is from the past to the future.

time we are generally referring to those quantities that vary *dynamically,* such that they are different at different moments of time. We will be exploring the role of time in the dynamical equations of physics in the next chapter.

Does Time Flow?

The physicist Paul Davies dismisses the notion of a flowing time thus: 'Attempts to "graft on" a mysterious extra quality to bestow a flowing motion upon time which is simply "there" is reminiscent of attempts to explain the vital quality of living organisms by adding a "life force" or "elan vital" to otherwise lifeless matter'.[9] While we have the strong sense

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FIGURE 3. If we do float along the river of time, we do so with our backs to the future, watching the past receding away from us.

that we are moving *through* time—or conversely that time flows past us—this sensation of flowing time seems to be an entirely subjective experience. After all, what could actually be flowing? If time flows then that would suggest it should be flowing at some rate, but what would we measure that rate against? Does time go by at a rate of one second per second? What does that even mean? And if it is our consciousness moving along some sort of static time axis, then how fast is it moving, and what (external) measure of time do we need to define this rate? The very notion of a rate of change is itself embedded within time.

What does modern science have to say about all this? It is one thing to argue that there is continuous change along the time axis, or that moments are organised in a certain temporal order, but quite another

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to pin down exactly where in our objective description of reality it is that time flows in the way we experience it. The answer is that modern science has nothing whatsoever to say about the flow of time! The flow we experience in manifest time is completely absent in physical time. The closest physics gets to the notion of flowing time is in the theory of relativity where two observers, either moving relative to each other or experiencing different strength gravitational fields, disagree on how 'fast' the other person's clock is ticking relative to their own. I will discuss this in greater detail in Part II.

In general, while time is an integral part of our mathematical description of nature, nowhere in our laws or equations of physics is there any hint that it actually 'flows'. In our everyday language we say that 'time passes', 'the time will arrive', 'the moment has gone' and so on. But we only *sense* that time flows. All that actually exists according to physical time is an ordered sequence of events: states of reality defined at different points (moments) on the time axis.

Consider what we do when we wish to describe the speed of a certain process. We either count the number of events in a given interval of time, such as the number of heartbeats per minute, or the amount of change in an interval of time, such as how much weight a baby has put on in one month. Time is the measuring stick against which we quantify change.

But if we look deeper at the equations of physics that allow us to calculate this change, we see that time comes in merely as a parameter: the symbol, t, that can take on any value. For example, a particle has a certain position, or is moving at a certain velocity, *at a given value of t*. These dynamical equations of motion then allow us to compute what the particle is doing at any other time, whether in its past or its future. In this way, we can see how the particle's state changes, in the sense that it is different at different times. But these states of the particle at different times are themselves just snapshots at certain instances. There is still no flowing time.

It certainly seems that the strong sense we have of time continuously flowing from past to future is indeed just an illusion, however real it might seem to us. But while science is unable to provide a satisfactory

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explanation for this strong sense we have of passing time, and of a changing present moment, some physicists and philosophers think this is because there is something missing in the laws of physics.

They may just turn out to be right.

Is Time Continuous?

Our experience of *flowing* time should not be confused with our experience of time as a *continuum* (as opposed to being made up of a discrete set of individual moments). But the notion of time flowing and time as a continuum are addressed together in the following famous idea. Another Greek philosopher and a student of Parmenides was Zeno of Elea. Like his teacher, Zeno believed that we cannot always trust our sense experience in order to understand the world, but that we must instead rely on logic and abstract reasoning. Aristotle, who lived a century after Zeno and from whose writing we have learned much about him, regarded Zeno as the founder of dialectics, a form of debate and argumentation that uses logic and reason to resolve disagreements.

Zeno is famous for a series of paradoxes that are brought to us by Aristotle in his great text, *The Physics*. There are believed to have been around forty in total, but only a handful survive. The one of interest here is known as the paradox of the arrow—which, like many of his famous paradoxes, is based on the idea that nothing ever changes, that motion is just an illusion and, just as his teacher Parmenides believed, that time itself cannot therefore exist.

The paradox goes like this. A flying arrow has, at any given instant in time, a certain position—a motionless snapshot. But by only seeing it at that instant, it will be indistinguishable from a truly motionless arrow in the same position. So how can we ever say an arrow is really moving? In fact, if time is simply a sequence of consecutive instants, in each of which the arrow is motionless, then it never truly moves. And yet we know the arrow does move. So, where is the error in Zeno's logic?

It may well be—and this is still a subject of heated debate—that time is indeed ultimately made up of a discrete sequence of infinitesimally short 'moments', which we can think of as the smallest possible,

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indivisible, intervals of time, or 'quanta' of time. But if these indivisible intervals are not exactly of zero duration (that is, if they are not true snapshots), then the arrow will be in a slightly different position at the start and end of each interval and cannot be said to be at rest. On the other hand, if these snapshots are truly of zero duration, then it does not matter how many of them sit together side by side, for they will never add up to a non-zero interval of time; we can add zero to itself as many times as we like, and the answer is still zero.

It would take the invention of calculus and the idea of infinitesimals developed by Leibniz in the seventeenth century to lay the paradox of the arrow to rest, for it showed how many finite but tiny intervals of time can, as they each shrink to zero duration, give rise to a continuous stream, just as a line in space is made up of an infinite number of discrete dots, but is itself continuous.

So, treating time as a smooth continuum is no different from treating distances in space as a smooth continuum.

This still doesn't help us with the issue of whether this continuous time *flows*. After all, space is a continuum and yet it just 'sits there', not doing anything. So, what is it about time that we experience as flowing or changing that we do not have with space? Well, again, if we had a simple answer to this question I wouldn't have bothered writing this book.

The Direction of Time

Just as we have a sense that time flows, it seems obvious that this flow must also have a direction, pointing from past to future. We remember the past and look ahead to an unknowable future. But where does this directionality come from? Like the flow of time, you might be wondering why this is even a question that needs answering. Surely, asking why the past comes before the future is a tautology. What we mean by the word 'before' *is*, by definition, the past. But we can make this a little more meaningful if we talk about two events, say, with one being the cause of the other (for example, you flick on a light switch and then a light comes on). Here it makes sense to say that the flicking of the switch

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is in the past of the light coming on. The order of the two events cannot be swapped over in time: cause and effect.

All around us, we perceive events (things that happen) arranged in one temporal direction rather than the other. An ice cube placed in a glass of warm water will melt while the warm water cools down, but we never see a glass of room-temperature water spontaneously forming an ice cube floating on its surface while the rest of the water warms up. This process of heat transferring from the warm water to the cold ice cube gives a direction to time.

There are plenty of examples of processes like this that never happen in reverse,* so you may be forgiven for thinking that this irreversibility is just a feature of reality that needs no further explaining—if it weren't, that is, for a major spanner in the works.† You see, all our fundamental equations of physics that describe how things change are symmetric in time. The fundamental laws of nature suggest that the world can run equally well forwards and backwards in time. So, the challenge is to understand where this irreversibility, or arrow of time, comes from.

Whether time is real, whether it flows, whether it is continuous, why it only points in one direction and why the past is not the same as the future, might all seem rather abstract and, while fascinating to contemplate, surely have no place in serious science. But, as we will discover, it turns out that the role of time in physics is even more baffling.

Time According to Physics

Until Isaac Newton completed his work on the laws of motion, debates about the nature of time were considered to be the domain of philosophy and metaphysics rather than science. But Newton described how objects move and behave under the influence of forces, and since all motion and change require time to make any sense, time had to be included as a fundamental part of his mathematical description of the

* Of course, this is not *entirely* impossible provided we waited long enough—longer than the age of the universe in fact—so technically we should not say 'never'.

† As we say here in the UK. I know American readers would say 'throw a wrench in the works'.

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world. Newtonian time is absolute and relentless; it flows at a constant rate everywhere in the universe independently of the events and processes taking place within space.

However, thanks to advances in physics over the past century, we now realise that time is a more complicated and subtle beast. Einstein showed, in his special theory of relativity in 1905, how time is unified with space to form four-dimensional (or 4D) spacetime. This profound merger meant that neither time nor space could any longer be considered as absolute or independent. And yet we should be careful not to regard time as just another 'direction'. We are free to move around in the three dimensions of space—less freely in the vertical direction here on Earth thanks to the constraints of gravity, of course—whereas the same cannot be said about time, for we are most certainly *not* free to go where we want on the time axis, but are instead shackled to our timeline, carried inexorably forward whether we like it or not. There is, at least subjectively, a huge difference between time and space.

In my book *The World According to Physics*,[10] which I wrote a few years ago and which was published just before the pandemic hit (I remember this because the week after it came out, the world went into lockdown and everyone had more important things to worry about than buying my book), I listed what I referred to as the three pillars of physics. These are the three broad physical pictures of the world, each valid within its own domain of applicability, that together give us our most accurate and powerful description of reality. First, we have quantum mechanics (or quantum field theory, to give it its more accurate modern name), which describes the behaviour and properties of the world of the very small: atoms and the subatomic domain. Then there is general relativity, Einstein's theory of gravity and spacetime, which is the framework we need for understanding the structure and behaviour of the universe at the largest scales. Finally, in between these two pillars, we have thermodynamics and statistical mechanics, which describe many familiar processes in our everyday macro world. I argued in that book that until we reconcile these three pillars of physics (a work in progress being carried out by many physicists today) and combine them into one

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unified picture of reality, we will never reach that holy grail of a 'theory of everything' that describes all physical phenomena.

For the purposes of the current book, I wish to modify my classification of the first two pillars of physics in order to highlight the outstanding problems in our understanding of the nature of time and how it enters into the different frameworks. With this new classification you will see that each of the three pillars gives us a very different definition of time.

The first pillar now represents the dynamical laws of physics: the equations that describe how something changes over time, whether they are those of Newtonian mechanics or of quantum mechanics. In fact, we have equations to describe all sorts of systems* that change over time, from the evolution of galaxies to the motion of tennis balls to the decay of atomic nuclei. In all these cases, the solution of the equation tells us what that system is doing, or what its properties are, at some particular value of time determined by the parameter, t, that appears in the equation. This t is referred to as 'coordinate time', and if we know the state of the thing we are describing *at that moment*, then we can use our dynamical equations to calculate its state at any other moment (at another value of t), which could be a time later than the original t (in its future), or earlier than it (in its past). Thus, coordinate time is no more than a mathematical *label* assigned to a moment in time within some pre-specified frame of reference† that allows us to define the state of the physical system we are interested in tracking.

The second pillar is Einstein's two theories of relativity, in which time is an inseparable part of the physical fabric of spacetime. In the first of these, known as the special theory of relativity, all observers, regardless

* I will be using the term "system" a lot in this book. While physicists will know exactly what I mean by it, I should make clear to non-physicists what it refers to. A system is basically some part of the world that we are interested in studying. It could an object, like a single particle or a glass of water, or a collection of objects, like a box of gas or a solar system. Essentially, a system is some part of the universe that we have chosen to partition off to analyse and which has certain properties that change over time subject to both its internal nature and external influences.

† That is, in relation to some reference time (five seconds after I started my stopwatch, two hours before midnight tomorrow, or ten billion years after the Big Bang, and so on).

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of how fast they are moving, will measure light to have the same constant speed. This strange postulate, which is not at all obvious, has the consequence that any two observers moving relative to each other will disagree on distances in space and durations in time such that the only way for them to reconcile their views is to combine space and time together into four-dimensional spacetime.

A decade after Einstein unified space and time in his special theory he completed his grander general theory of relativity, which describes how spacetime can curve and warp in the presence of matter and energy. That is, spacetime itself becomes malleable. In general relativity, time is no longer just an axis along which we experience change; it has a physical 'essence' in the sense that its 'shape' is influenced by the strength of the gravitational field.

Thus, in Einstein's relativity, time is more than just a number or label: It is a dimension—a part of the physical structure of four-dimensional spacetime. Our picture of reality according to Einstein becomes one in which all times co-exist: The past, the present, and the future are all equally real (just as all points along a line in space are equally real).

What then of our subjective feeling of change, of our consciousness drifting along the time axis as we experience an ever-changing present? Here is where manifest time and physical time diverge most dramatically. Flowing time and change become no more than an illusory impression, or sensation, that we feel as we creep along the time axis. And if change is relegated to a subjective experience, then we are back to the passage of time being something that only exists in our minds.

The third pillar is the subject of thermodynamics describing the properties of matter in bulk made up of large numbers of particles and giving rise to emergent properties such as heat, temperature, and pressure. Thermodynamics gives us a description of the world in terms of averages and probabilities. It deals with the transfer of energy from one place to another and from one form to another. Here, time is neither a dimension nor a label, but a *direction*, or arrow, pointing irreversibly from the past to the future. Such an arrow of time allows us to put sequences of events into order. The related field of statistical mechanics tells us that, at a fundamental level, this arrow is due to all systems'

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tendency to evolve, inevitably, from more ordered states to less ordered states: from special, primed states away from equilibrium towards equilibrium—ice cubes melt, cream mixes with coffee, smoke disperses, balls roll downhill, batteries discharge, and I grow older. Time points in the direction of this statistical inevitability. What could be more obvious than that?

My challenge in this book is not to propose a unified picture of reality with a single definition of time (if only!), but rather to tackle head-on two conceptual problems arising from these three very different ways of viewing time.

The 'Problems of Time'

Let us first take a step back. We have already seen that a fundamental problem to tackle is our inability to reconcile how we perceive time subjectively with what physics tells us about it—that is, how we connect manifest time with physical time. I will distil this issue into two *philosophical problems of time*:

1. Why do we perceive time to 'flow' when this concept is entirely absent in our physical theories and equations?
2. Why do we perceive the past to be so different from the future, each sitting on either side of 'now', when there is nothing special about the present moment in our physical theories and equations?

Then, there is a different category of problems surrounding the nature of time, which are the ones physicists try to address. These are the *problems of physical time*, to distinguish them from the above philosophical problems. Most of the attempts to establish time as an illusion have been built on the enterprise of unifying quantum mechanics (the theory of the microworld in which time appears simply as a parameter in the equations) with general relativity (Einstein's theory of gravity in which time is a dimension and part of the geometric fabric of 4D spacetime). Mathematical frameworks that attempt to unify these two pillars are known as theories of quantum gravity and include such exotically named ideas as *superstring theory*, *M theory*, *loop quantum gravity*, and

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causal set theory. There are others too, and while it is fair to say that some look more promising than others, it is also fair to say that none has emerged as the final word on the subject.

Among the various conceptual, mathematical, and observational challenges faced by attempts to unify quantum mechanics with general relativity, one of the most serious is generally referred to simply as 'the problem of time'. Here, I will call it *the first problem of physical time*, since there is a second problem that I wish to distinguish from it. This first problem arises because quantum mechanics and general relativity each treat time differently: one as a mere parameter, or label, and the other as a physical dimension.

An early attempt at bringing these two pictures together was based on work carried out by two American physicists, John Wheeler and Bryce DeWitt, who in 1967 came up with an equation[11] that bears their name and in which time is left out entirely. They were attempting to treat the curvature of spacetime in the language of quantum mechanics and had limited success, but the equation they came up with did not describe anything changing over time. I won't say too much about it here, but I feel I should give you something to get your teeth into.

As I mentioned earlier, the dynamical equations of physics, such as Newton's equations of classical mechanics, Schrödinger's equation of quantum mechanics, Maxwell's wave equation of electromagnetism, the diffusion equation, and many more, all describe different phenomena at different scales. But they have one thing in common: The quantities they allow us to calculate all change over time, as one might expect. In certain circumstances, however, the part of the equation that depends on time can be removed, leaving behind a simpler equation involving quantities that might change from one *place* to the next, but which are constant over time. An example of this is what every physics student learns as the *time-independent Schrödinger equation*, the solution of which (that is, the thing we solve the equation to find) is a mathematical quantity called the wave function, which tells us, for example, what the energy of a particular electron in an atom might be. This equation is the starting point in the derivation of the Wheeler–DeWitt equation, which

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is a 'relativistic' version of the Schrödinger equation in the sense that it incorporates gravity.

Well, actually, that's not quite right. The way the Wheeler–DeWitt equation is obtained is to start from Einstein's theory of gravity—his field equations that connect 4D spacetime with the matter and energy it contains—and apply the same approach that Schrödinger adopted in getting his equation from Newtonian mechanics: basically, 'making gravity quantum'. The solution of this equation is referred to as the wave function of the universe. Pretty ambitious, you might think. Well, yes, but what is interesting here is that, like the solution of the time-independent Schrödinger equation, the wave function of the universe doesn't change over time, and so it tells us nothing about how the real universe is actually evolving. It is a timeless equation and suggests that, viewed from the 'outside' (which of course is not possible), the physical state of the universe does not change, but for us observers imbedded within it, there is change all around us, including the stretching of the three-dimensional expanse of space over time—what we refer to as the expansion of the universe. But this suggests that if there were such a thing as a 'God's-eye view' of the universe from outside of spacetime, then no expansion would be observed, since that is just the way we perceive things from within it when we split space and time up and experience them differently.

For many working in the field of quantum cosmology, the timelessness of the Wheeler–DeWitt equation is not just an awkward theoretical curiosity, but something to take seriously. Indeed, Wheeler himself claimed that 'there is no spacetime, there is no time, there is no before, there is no after. The question what happens "next" is without meaning.'[12] This all sounds pretty damning for the reality of time, since John Wheeler was truly one of the greats of twentieth-century physics and his views should never be dismissed without good cause. We will see later on that it may indeed be that time emerges from the Wheeler–DeWitt equation only in a classical approximation of a deeper quantum realm.

The Wheeler–DeWitt equation isn't the only example of a mathematical attempt to remove time. The British physicist Julian Barbour is

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another who has followed in the tradition of Parmenides and Zeno. Barbour has also argued that the universe is timeless and all that exists is a collection of individual moments.[13] Here is a summary of the main argument he makes. Imagine snapping your fingers (event A), then snapping them again (event B). We have the impression that B followed A because at the time of B we have a memory of A. However, this memory is not the same thing as experiencing time passing between A and B. All of existence, according to Barbour, is made up of equally real static moments. No one of them is any more real than the others, nor is there even any necessary order to them.

I know I am not doing Barbour justice with this very brief summary; nevertheless, surely, you might think, the fact that these events happen *at different times* is sufficient reason to believe that time *has* to exist. Unfortunately, this is not a sufficiently strong argument for the existence of time.

But if relativity theory tells us that time is a static dimension and that there is no such thing as the 'passage' of time, then surely the physics of the first pillar (the dynamical laws and equations of motion that describe how the world and everything in it changes with time) can rescue it from the ignominy of just being a product of our subconscious. Well, here too we are faced with a major difficulty. This is *the second problem of physical time*. You see, all those fundamental dynamical equations of physics I listed have a surprising feature in common: They evolve *symmetrically* in time. By this I mean that if you describe what something is doing at any given moment in time (whether it is the motion of a planet, the swing of a pendulum, or the state of an electron) then it makes no difference whether you 'evolve' the equation* forwards or backwards in time; it predicts that the system will change *in the same way*. That is, in all these equations of physics, and subject to certain subtleties I don't want to get into here, time can point in either direction and these

* By 'evolving an equation' I mean the following: One starts off plugging into the equation some initial state of the system (the thing it is describing) at some moment in time (for the equation this is some value of the time parameter, t); then the equation is solved to find the state of that system for some other value of t, which could be in what we think of as the past or the future of t.

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equations would predict a physically permissible evolution in time of the system they are describing, in the sense that if we were watching a system evolving according to these equations we would not be able to say whether time is running forwards or backwards. We say that such dynamics are *time-reversal invariant*. This is of course rather frustrating since we see all around us a clear difference between the past and the future. So, what is going on?

If you start by describing a system (for example, inert gas molecules in a box all moving around and bumping into each other) at some time, t, and you evolve the dynamical equation that describes the state of these molecules (their positions and speeds) forward in time so that it predicts their state at, say, $t + 10$ seconds, then you will find that their predicted state looks exactly the same as it would if you crank the handle backwards to work out what they were doing at $t - 10$ seconds. Basically, because such equations run equally well forwards and backwards in time, they don't pick out a direction; the future and the past on either side of your starting time (t) look exactly the same. This is often explained in terms of watching a movie of the process and not being able to tell if it is running forwards or backwards. The immediate, sensible conclusion to draw is that the equations are just wrong; yet they work perfectly well if we were to check their prediction of the future by performing a measurement on the real system. We cannot check the prediction of the state of the system in the past since such a check would have required us to carry out a measurement at that moment in the past, which would have affected the way the system evolved, such that it would have ended up in a different state at time t!

Such symmetry in time is not only in conflict with our experience (manifest time), but also with one of the most sacred laws of physics, which underpins that third pillar. It is called the *second law of thermodynamics* and is intimately connected with a quantity called *entropy* that, according to the second law and when describing a system in isolation, can never decrease.

But we don't need to appeal to the rather abstract concept of entropy to see this conflict between the fundamental dynamical equations of physics and the second law of thermodynamics. We observe all around

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us irreversible processes obeying the second law that would look crazy, or at least highly unlikely, if we saw them in reverse (like watching a movie backwards). For many physicists, the issue is resolved by tagging onto the second law an extra ingredient called a *boundary condition*, which means that if we start any system off in some special state at starting time (t), then it will of course evolve symmetrically (forwards and backwards) in time. But if we push that boundary condition back to the very beginning of time (an assumption known as the *Past Hypothesis*, which states that the universe, for reasons yet to be made clear, started off in a state of very low entropy) then we don't have to worry about violating the second law, since running time backwards to before the universe was born makes no sense. No one knows why the universe should have started in such a special, low-entropy state.

In summary, then, the two problems of physical time—as distinct from the philosophical problems of time discussed earlier—are the following:

1. How do we reconcile the notion of coordinate time (or time as a parameter) that appears in the dynamical equations of physics, such as those of Newtonian mechanics and quantum mechanics, with time as a dimension in relativistic spacetime? This problem is central to our efforts to unify quantum mechanics with general relativity to reach a theory of quantum gravity.
2. How do we reconcile those same time-symmetric dynamical equations of physics with the irreversibility of thermodynamics and other processes that give us an arrow of time?

Arrows of Time

As well as what is called the thermodynamic arrow of time that points in the direction of increasing entropy (or disorder)—the cooling down of hot bodies, cream mixing with coffee, melting ice cubes, dispersing smoke, and so on—there are other arrows set by different physical processes. For example, there is a radiation arrow of time pointing in the direction of radially expanding electromagnetic waves (such as light), which

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always spread outwards from a source just like the ripples you see when you drop a stone into a pond. You never see waves converging on their source. Then there's the measurement arrow of time in quantum mechanics, which points in the direction of the so-called collapse of the quantum state when it is observed; or the cosmological arrow pointing in the direction of the expansion of space. There is even a more basic causal arrow of time pointing from causes to effects and not the other way round.

However, saying there are different arrows of time is like saying there are different kinds of time. Can we not find that one fundamental 'source' of irreversibility: a primary arrow of time? In other words, is there a physical process that gives us the irreversibility we crave in the first place which, once set, defines how all other irreversible physical processes follow suit?

The job of physics is to describe reality, and we have done pretty well in this endeavour so far even if there is still much that we have yet to figure out. But maybe there are some aspects of the universe that we will never be able to explain, or that turn out not to require explanation because they just *are*.

But while there are still many mysteries to solve, we have come a long way since Parmenides, Zeno, and Heraclitus, and this is the journey I wish to take you on in this book. I will introduce the physics and examine the consequences of each of the three pillars and the role played by time in each. Then, in the final few chapters, I will attempt to weave together the different strands to see if there might be a glimmer of hope in our understanding of time.

Spoiler Alert

Let me at least lay my cards on the table here and state my position so that you know what you are getting yourself into. If you violently disagree with me, you may not wish to continue reading the book, but I hope you will hear me out. My conclusions are, to a large extent, aligned with the consensus modern-day position on the nature and origin of time that we have reached through our increasing scientific understanding, but they are also partly my own personal views on the subject.

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Many experts in the field would argue that mine is a minority view on certain issues, but that is fine since these are still open questions. Anyway, in summary, I will be arguing the following:

- Our perception that time 'flows' is indeed an illusion, but it may be the only illusion.
- While time may turn out to be an emergent property from some more fundamental description of reality buried deep in the timeless quantum realm, it nevertheless exists independently of our subjective experience. The final, correct theory of quantum gravity may turn out to be timeless, but that only has meaning if we are describing the universe as a whole from the 'outside'. Within the universe, which after all contains all of existence, time is real.
- There are many ways of defining an arrow of time; some are subjective, depending on how we look at the world, while others are harder to explain away. But maybe there is one master arrow of time baked into the universe from the start and all other arrows of time point in the direction they do (from our past to our future) as a consequence of this master arrow. The origin of this master arrow may lie in the one truly irreversible process in nature: quantum decoherence.
- While the standard argument made by most cosmologists is that the arrow of time is a result of very low entropy at the Big Bang (what is called the 'Past Hypothesis'), I propose a different way of looking at it. Firstly, I will suggest that the Past Hypothesis is not a bolt-on to the so-called 'fine-tuning' of the initial conditions (that the laws of physics and fundamental constants of nature had to be just right to give rise to the universe we see today), but rather that the low entropy of the early universe is a natural *consequence* of this fine-tuning. Secondly, I will propose a different Past Hypothesis to the standard thermodynamical one: one based on quantum entanglement.

Well, I'd better let you read on to decide for yourself how persuasive I am.

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