

# What Comes After the Dark

*The Far Future of the Universe,*
*in Plain Words*

Forrest Landry

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# The Question of the Far Future

## A Clear Night

How does the universe go on, long after us? Stand on your back step on a clear night, away from the lights of a town, and look up. You see stars, and here and there a faint smudge that is another galaxy: an island of billions of stars, far beyond the stars of our own galaxy. Everything you can see in the night sky is something you can set beside something else, to find which of the two is brighter and which fainter, which nearer and which farther, which still and which moving. In this book, to compare two things is to set the two side by side and find whether the two are the same or different. Every chapter of this book uses one picture: the sky over your back step, which is the world you can see and compare with.

Popular books on the end of the universe describe a few endings. The galaxies might stop moving apart and fall back together in a Big Crunch. The universe might go cold and dark for ever, with nothing left to happen, in what physicists call a heat death. The galaxies are moving away from one another, and their spreading might grow strong enough to tear everything apart in a Big Rip. Empty space itself might change into something else. Or the universe might shrink, rebound like a dropped ball, and begin again.

This book is one of a collection of books on physics that I have written. I work out the physics of the world, in the books of that collection, from the act of comparison itself. In the chapters of this book, the words "this physics" mean the physics that I work out in that collection of books. I describe each of the five endings in turn (the Big Crunch, the heat death, the Big Rip, a change of empty space into something else, and a rebound that

begins the universe again), and for each ending I say what this physics predicts, and why. A reader has further questions after hearing the endings, so I ask those questions too. What becomes of matter, and of anyone still there to watch? Can a mind keep thinking for ever? If the universe has one long era after another, what crosses from one era to the next, and could anything escape the end of an era?

## The Answer, in Brief

This book's answer has two parts. The sky does empty over a very long time, but the long emptying of the sky is *not* the end. Astronomers reckon that the sky empties over a hundred billion to a trillion years, and the sky empties for anyone, anywhere: wherever a person stands, the sky that the person can see and compare with empties. Two of the popular endings do not happen: nothing falls back together, as in a Big Crunch, and nothing is torn apart, as in a Big Rip. Empty space carries a small hidden geometry at every point, and the hidden geometry has no other shape to change into.

A black hole is a region from which nothing, not even light, can return. Chapter 1 introduces black holes. Chapter 8 describes what happens at the end of a black hole's inside. The hidden geometry of empty space holds the forms that matter has, such as atoms, stars and bodies, so matter keeps those forms until the hidden geometry itself is no longer held. The hold on the hidden geometry ends in two cases only: at the end of a black hole's inside, and for a body carried away alone (a body carried beyond the reach of all other matter). When the emptying is complete, a new world begins from the place where the insides of the old world's black holes end, and the same laws of physics as in the old world hold again in the new world. I go through each step of this answer in the twelve chapters of the book, one question at a time.

## How the Book Speaks

I have written this book for an interested reader who has studied no physics beyond what is taught at school. I explain in plain words every word that a physicist would use, and I set the word in italics where the word first appears. The Key Concepts are at the back of the book. The Key Concepts are a reminder of the explanations in the chapters, and not a replacement for those explanations.

The twelve chapters contain no equations. Where a relation between quantities matters, I first give a picture that shows why the relation is needed. Then I state the relation in words, in one sentence. Appendix A, "For the Specialist", contains the reasoning in full, together with the place in the collection where each step is argued and the measured values with their sources. Appendix B says what the coming measurements will measure, and what this account predicts those measurements will find. You can read the twelve chapters without either appendix.

Where I state my own reading of something, I say so, in the first person. Where the book reports what astronomers and physicists have measured or calculated, the book says so, and the References at the back of the book contain the paper for each reported measurement or calculation.

## The Shape of the Book

Part One, "The Long Emptying", is about the sky over the back step, as the galaxies move apart and the sky empties. The first four chapters of Part One ask what happens to the sky we can see, whether everything falls back together, whether everything is torn apart, and whether empty space changes into something else. The last three chapters of Part One ask what becomes of the stars and their ashes, of someone who is still there watching, and of a mind that wants to go on thinking for ever. Part Two, "After the Dark", is about what comes after the long emptying of the sky.

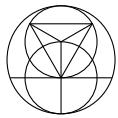
The first four chapters of Part Two ask why the emptying is not the end, what crosses over into the next world, whether anyone could escape the end of our era, and whether the emptying and the new beginning have happened before. In the last chapter, Chapter 12, I go through the whole answer once more in one view.

I open each chapter on one question. I end each chapter except the last on the opening question of the next chapter. I end the last chapter on the sky. The first question of the book is the question you ask on the back step, looking up at the night sky.

What happens to the sky we can see?

# PART ONE

*The Long Emptying*



Chapter 1

# What Happens to the Sky We Can See?

## The View from the Back Step

What happens to the sky we can see? The question begins on the back step of a house. Picture yourself on the back step on a clear night, far from the lights of town. Give your eyes twenty minutes to adjust to the dark, and the sky fills in with light. You see the bright stars first, and then the fainter stars. Then the pale band of the Milky Way appears across the middle of the sky. The pale band is the great disc of stars that we live inside, seen edge on from within. The disc is our *galaxy*: an island of a hundred billion stars or more, held together by its own gravity, with wide dark gulfs between our galaxy and the next islands. From the back step, every single star you can pick out belongs to our own galaxy.

Some of the other islands are in the sky too, if you know where to look. In the autumn sky of the northern half of the world, in the constellation Andromeda, your eyes alone can find a faint oval smudge. The faint oval smudge is the Andromeda galaxy, the nearest large galaxy to our own, and the light of the smudge is the light of a great many billions of stars blended into one soft glow. A pair of binoculars shows a few more smudges. Point a large telescope at a dark patch of sky that looks empty to the eye, and the telescope finds the patch crowded with faint galaxies, each galaxy an island like ours.

Count the smudges, then, as far out as your eyes and your instruments can see. You can set each smudge beside the others: one brighter and another fainter, one nearer and another farther. In this book, to *compare* one thing with another is to set the two side by side and find whether they are the same or different. Throughout this book the view from the back step pictures one thing: the world that someone standing there can see and compare with. Tonight you can see and compare a great many galaxies from the back step. Over a human lifetime the count of galaxies stays the same, but over a hundred billion to a trillion years the count falls, and the sky you can compare with thins. What happens to the sky we can see is, first of all, what happens to the count of galaxies.

## Twenty-Four Islands

How do we know that the galaxies are moving at all? Edwin Hubble was an astronomer at the Mount Wilson Observatory in California, and in January 1929 Hubble sent a short paper to the *Proceedings of the National Academy of Sciences*. In the paper Hubble set two lists side by side. Astronomers then called galaxies "nebulae". The first list gave how fast each of a set of faint nebulae was moving toward us or away from us, and the second list gave how far away each nebula was. Speeds were easier to come by than distances, and Hubble gave the two counts: "Radial velocities of 46 extra-galactic nebulae are now available", he wrote, "but individual distances are estimated by only 24". A radial velocity is a speed straight toward us or straight away from us. Hubble found a pattern in the twenty-four galaxies whose distances he had. The farther away a galaxy was, the faster the galaxy was moving away from us. Hubble wrote that his results "establish a roughly linear relation between velocities and distances among nebulae". A *linear relation* is the simplest kind of relation there is: twice as far, twice as fast. Hubble also reported that his colleague Milton Humason had begun to measure the speeds of still fainter and more distant galaxies.

Astronomers measured the speeds from the colors in the light of each galaxy. The light of a galaxy carries the marks of the chemical elements in the stars of the galaxy: thin dark lines at fixed colors, and each of those colors is the same in every laboratory on Earth. In the light of the distant galaxies, the dark lines sat shifted toward the red end of the rainbow. Astronomers call a shift toward red a *redshift*: the stretching of light into longer, redder waves on the way to us. Hubble read the redshifts as the speeds at which the galaxies were moving away.

Astronomers now read Hubble's pattern as the *expansion* of the universe: the distances between galaxies that are not held together by gravity grow with time, because space itself is stretching. Space is like a room that is itself growing: the galaxies sit in the room and are carried apart by the growth of the room, rather than flying apart through a fixed, empty room. Light that crosses the growing room is stretched along with the room, and the stretching of the light is the redshift. The stretching of space gives exactly Hubble's pattern, because a galaxy twice as far away has twice as much stretching space between the galaxy and us, and so the galaxy recedes twice as fast. At a given time, every galaxy recedes at the same speed for each unit of its distance from us. Astronomers call the speed of receding for each unit of distance the *expansion rate*. The expansion rate says how fast the universe as a whole is growing.

## Faster, Not Slower

Is the expansion slowing down, as you would expect from gravity? For most of the twentieth century astronomers expected the expansion to slow down. Every galaxy pulls on every other. So gravity should brake the expansion, the way gravity slows a ball thrown upward. The only open question seemed to be how hard the brake of gravity was pressing. In the 1990s two teams of astronomers set out to measure the braking with exploding stars. A *supernova* is a star that blows itself apart. For a few weeks a supernova can shine as brightly as a whole galaxy. One kind of super-

nova explodes with very nearly the same true brightness every time. So astronomers can tell how far away a supernova of that kind is from how faint the supernova looks from Earth, as the faintness of a lamp of known brightness tells how far down the road the lamp stands.

Adam Riess was a member of the team led by Brian Schmidt, and in the autumn of 1997, at the University of California at Berkeley, Riess was working through the team's measurements of distant supernovae. The distant explosions looked too faint for a universe whose expansion was slowing. Riess later recalled that his first fits, the calculations he matched to the measurements, worked only with something pushing the expansion faster, as if gravity had turned into repulsion. Riess spent a long time checking his work, and found no error. Riess told Schmidt first, and Schmidt checked the final calculations and reached the same result as Riess. The team's paper of 1998 reported that, on average, the distant supernovae were ten to fifteen percent farther away than in a slowing universe. Saul Perlmutter, at the Lawrence Berkeley National Laboratory, led the other team. Perlmutter's team measured forty-two distant supernovae and found the same result as Schmidt's team. The expansion is speeding up. In 2011 Perlmutter, Schmidt and Riess shared the Nobel Prize in Physics for the discovery that the expansion is speeding up.

Astronomers call whatever drives the speeding up *dark energy*: dark because dark energy gives off no light, and energy because dark energy acts on the expansion as an energy does. The simplest form that dark energy can take is a *cosmological constant*, which astronomers define as an energy of empty space itself. A cosmological constant is the same amount of energy in every cubic meter of space, everywhere, and at every time in the history of our universe, and a cosmological constant does not thin out as space grows. Albert Einstein first wrote a constant of this kind into his equations of gravity in 1917, to hold his model of the universe still. The constant found in 1998 does the opposite: the constant speeds the expansion up. Matter thins out as space grows, because the same matter is spread through more room. The energy of empty space does not thin out. So, as the universe grows, the cosmological constant comes to outweigh

the matter. Once the constant outweighs the matter, the expansion speeds up and keeps speeding up. Both teams found that the supernova measurements favored a cosmological constant that is positive. In the physics of this book, the dark energy is exactly a cosmological constant: one number, fixed once. Chapter 2 shows why the cosmological constant cannot change, and Chapter 3 shows why the push of the cosmological constant never grows.

## The Edge of What You Can Ever See

How far can anyone on the back step ever see? To answer, this book needs a word for whoever stands on the back step. In this book an *observer* is anything that compares one thing with another and registers the result: you on the back step, an astronomer at a telescope, a camera, a photographic plate. Anything inside the world can fill the role of an observer, and filling the role does not need a mind. The fact that an observer needs no mind will matter in Chapters 6 and 7, which follow the observers of the far future, long after there is anyone like us to look up.

Picture the speeding expansion from the back step: each distant galaxy recedes faster as time goes on. Beyond a certain distance, light that a galaxy sends out today will never reach you, however long you wait, because the space between you and the galaxy grows faster than the light can cross the space. The *cosmological event horizon* is the boundary beyond which no event can ever send a signal to a given observer, and this book usually calls the cosmological event horizon simply the *horizon*. For you on the back step, the horizon lies at the distance beyond which light sent out today never reaches you. Every observer has its own horizon, centered on the observer, as each walker on a wide plain carries a skyline wherever the walker goes: the walker is the observer of the picture, and the skyline is the horizon.

A galaxy that drifts across your horizon fades out of your sky gradually, not at once. You still receive the light that the galaxy sent before crossing your horizon. You can still compare the old light with the rest of your sky. The galaxy fades from your sky because the old light arrives ever more stretched and ever dimmer, without limit. The galaxy's present and future can never reach you after the galaxy has crossed your horizon. So the galaxy's present and future stay outside every comparison with you.

An observer's *outside world* is everything that the observer can ever compare with. The outside world is the whole of what can ever reach the observer and be set beside the rest of what the observer receives: every star, galaxy and glow whose light or signal arrives, now or later. Your outside world includes the light that a galaxy sent before crossing your horizon. After the crossing, the galaxy's present and future do not belong to your outside world. So for every observer the outside world has a boundary, and the observer's horizon is the boundary.

## Clumping and Departing

What happens to the matter inside an observer's horizon? Inside your horizon, gravity gathers matter into clumps. Stars form, burn out, and leave remains behind. The remains pull in more matter and merge, and much of the bound matter, the matter that gravity holds together, ends in black holes. A *black hole* is a region in which matter is packed so densely that nothing, not even light, can climb back out of the region. Physicists also call the boundary of a black hole a horizon: the surface from inside which no signal can reach the outside. The boundary of a black hole shares the name with the cosmological horizon because each boundary is an edge past which no signal can reach a given observer. Where a reader could doubt which horizon is meant, this book says "the black hole's horizon" or "the cosmological horizon". A bound clump loses the rest of its matter, the matter that does not end in a black hole, as bodies flung out or

as *radiation*: light and other rays that carry energy away. The expansion carries everything that is not bound to an observer's own clump beyond that observer's cosmological horizon.

From the back step, the smudges you see fall into two groups. One group is bound to our galaxy by gravity, and the other group is not. The Andromeda galaxy is bound to our own galaxy by gravity. Our galaxy and Andromeda belong to one small family of galaxies bound together by gravity, which astronomers call the *Local Group*. The Local Group holds our galaxy, Andromeda, and some dozens of smaller galaxies. Because Andromeda is bound to our galaxy, the expansion will never carry Andromeda away from us. The fainter smudges that binoculars and telescopes find lie outside the Local Group, and the expansion carries every one of the fainter smudges away. Astronomers have followed the standard calculation of the expansion forward in time, and the astronomers report that the sky beyond our own Local Group empties out of reach in a hundred billion to a trillion years.

Over far longer times still, the Local Group's stars burn out. Every bound clump of the Local Group ends inside a black hole or flings its bodies away into the dark. So, in the end, everything in the sky comes to one of two fates. A thing in the sky either falls into a black hole, or the expansion carries the thing beyond the reach of all other matter, with everything else gone beyond the thing's own cosmological horizon. I call the second fate being "carried away alone". A watcher on the back step comes to one of the same two fates: falling into a black hole, or being carried away alone. Chapter 6 follows the watcher to the end.

## The Slow Glow of a Black Hole

Do black holes at least last for ever? In 1975 the physicist Stephen Hawking published a calculation showing that black holes do not last for ever. Hawking's calculation shows that a black hole gives off a faint warmth, as if the hole were a hot body at a definite temperature, and that

the heavier the hole, the colder the hole glows. Hawking wrote that for a black hole with the mass of the Sun, the temperature of the glow is much lower than the temperature of the afterglow of the Big Bang, which is about three degrees above absolute zero.

Three terms in Hawking's comparison need a gloss: the Big Bang, the afterglow, and absolute zero. The *Big Bang* is the hot, dense beginning that the history of our universe runs back to, as astronomers piece the history together. The *afterglow* is the faint warmth left over from the Big Bang, and the afterglow reaches us from every direction in the sky. Astronomers call the afterglow the *microwave background*, because the expansion has stretched the light of the afterglow into microwaves, waves far longer than the ones our eyes can see. *Absolute zero* is the coldest any temperature can be, the temperature of a thing with no warmth to give at all.

When a black hole is colder than the space around the hole, the hole takes in more warmth than the hole gives off. So the hole grows rather than shrinks. The hole begins to lose more than the hole gains only after the afterglow has cooled below the hole's own temperature. The afterglow cools as space grows, and for a hole of the Sun's mass the standard calculation puts the moment when the afterglow becomes colder than the hole hundreds of billions of years from now. Once the hole begins to shrink, the shrinking takes far longer. In 1976 the physicist Don Page worked out how fast a black hole loses its mass to Hawking's glow. For a hole with the mass of the Sun, Page's figure is about two times ten to the sixty-six years: a span of years written as a two followed by sixty-six zeros.

Set the two spans of time side by side: the emptying of the sky, and the glowing away of a black hole. The sky beyond our own Local Group becomes empty in a hundred billion to a trillion years, while a black hole of the Sun's mass glows itself away in a number of years sixty-seven digits long. The emptying comes first, by an enormous margin. Hawking's glow is real, but on the time scale of the emptying the glow is far too slow to change anything.

## Astronomers Who Will See No Expansion

What could astronomers learn about the universe in the far future, after the sky beyond their own galaxy has emptied? In 2007 Lawrence Krauss and Robert Scherrer asked what astronomers of the far future could learn. Krauss and Scherrer are physicists. Krauss and Scherrer pictured observers living in the single galaxy that the Milky Way and Andromeda will by then have become. The calculation of Krauss and Scherrer puts every galaxy outside the merged galaxy beyond the horizon by about a hundred billion years from now, which is the near end of the span of a hundred billion to a trillion years. The observers in the merged galaxy would have no distant galaxies whose redshifts they could measure, and so no Hubble pattern to find. By about a hundred billion years from now, the expansion would have stretched the afterglow of the Big Bang into waves about a meter long. Much later the expansion would stretch the afterglow into waves longer than the horizon itself. No instrument can catch a wave longer than the horizon. Krauss and Scherrer wrote that the observers "will conclude the existence of a static 'island universe'": one galaxy, alone, in an unchanging dark. *Cosmology* is the science of the universe as a whole. Krauss and Scherrer called the future they pictured "the end of cosmology and the return of a static universe". Hubble had twenty-four galaxies to work with, while the astronomers of the merged galaxy would have none beyond their own.

Why would the astronomers of the far future learn so little? Light takes time to travel. So a photograph of a star shows the star as the star was when the light left the star. Everything a person knows of the past arrives in the same way as the starlight, as evidence that the person receives now: old light, the afterglow, the records of instruments. In our own time as in any other, every astronomer pieces together each picture of the past from evidence that the astronomer receives now. Today the sky above the back step is crowded with evidence: distant galaxies with their redshifts,

the afterglow from every direction, the supernovae that showed the speeding up. The astronomers whom Krauss and Scherrer picture will receive the light of their own island galaxy as evidence, and nothing more. The distant galaxies carried the evidence of the expansion. By then every one of the distant galaxies will have left the outside world of the far-future astronomers. Krauss and Scherrer's "end of cosmology" is the emptying of the sky as seen from the desk of an astronomer.

## A Passing Stage

By the populated sky I mean the sky full of galaxies above the back step. In this book an *epoch* is one era of the world, in which stars, galaxies and black holes form. I use the word 'epoch' because our era is not the only era: Part Two of this book shows how one era of the world gives way to the next. Our own epoch is the era whose history runs back to the Big Bang.

The sky full of galaxies belongs to our epoch. For every observer, the outside world has a boundary, the cosmological horizon. Inside the horizon, matter ends inside black holes or departs, and the expansion carries whatever is not bound beyond the horizon, so every observer's outside world empties over a long enough time. Each observer's outside world belongs to the time in which the observer's sky is still full of other things to compare with. The outside world is not eternal. The populated sky is a passing stage of our epoch.

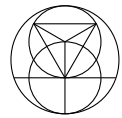
Every step of the emptying is physics that astronomers have measured and calculated: the speeding expansion, the horizon, the clumping of matter into black holes, and the slow glow of black holes. The chapters that follow are about what the emptying leads to. The history of the universe goes on after the emptying, and in Chapter 8 I show why.

## What This Means for You

Tonight there is a great deal in the sky above the back step to see and compare with. The smudge of Andromeda will stay with our galaxy, because gravity binds Andromeda to our galaxy. The fainter galaxies, which only binoculars and telescopes show, are on their way out of the sky that anyone in our own galaxy will ever be able to compare with. Astronomers of our time can see the expansion, measure the speeding up of the expansion, and read the afterglow of the Big Bang, because astronomers of our time live while all three are still in view. The populated sky is real, and the populated sky belongs to now.

> **Key idea.** The expansion of the universe is speeding up, driven by a cosmological constant, and so every observer has a horizon beyond which nothing can ever reach the observer. Inside the horizon, matter clumps into black holes or departs. The expansion carries everything beyond the Local Group, our own small family of galaxies, out of reach in a hundred billion to a trillion years. Black holes glow themselves away only in about two times ten to the sixty-six years, so the emptying comes first. The populated sky is a passing stage of our epoch. The passing of the populated sky matters for the question of this book, how the universe goes on long after us, because the far future begins as an emptying sky, and every later chapter is about what the emptying leads to.

Gravity pulls every galaxy toward every other. Will all the galaxies one day fall back together?



Chapter 2

# Will It All Fall Back?

## A Ball Thrown Upward

Will everything fall back: will the galaxies of the sky one day fall back together? Stand on the back step again, as in Chapter 1, and look at the faint smudges of the distant galaxies. Every one of the distant galaxies is moving away from you. The expansion of the universe carries the distant galaxies away, and Chapter 1 described the expansion as the stretching of space itself. Every one of the distant galaxies is also pulled back toward you, and toward every other galaxy, by gravity. So you may well ask whether the smudges will one day stop receding, turn around, and come back toward you, because gravity pulls back on every galaxy that the expansion carries away.

Throw a ball straight up from the back step. The ball rises, slows, stops for an instant at the top, and falls back into your hand. Throw the ball hard enough, from a small enough world, and the ball never comes back: the ball slows for ever and never stops. There is one dividing speed between the throw that falls back and the throw that never comes back, and a ball thrown at exactly that speed slows for ever and never quite falls back. For most of the twentieth century astronomers pictured the expansion of the universe in just the way of the thrown ball, with the galaxies as the ball and the gravity of the matter between the galaxies as the pull of

the world. If the galaxies were thrown apart too gently for the amount of matter between them, the pull of that matter would win, and the expansion would stop and reverse, and the whole of space would fall back together into a hot, dense end. Physicists call that falling back a *recollapse*: the expansion of the universe as a whole stopping, turning around, and contracting all of space together. Popular books call the hot, dense end of a recollapse the Big Crunch.

Our epoch does not fall back. Our epoch is the era of the world whose history runs back to the Big Bang. A recollapse could come about in three ways: from enough matter, from a changing cosmological constant, or from all space collapsing at an epoch's end. This physics has a reason of its own against each of the three ways. We begin with the picture of the universe in which a recollapse first became possible.

## A Letter from Petrograd

Where did the idea of a universe that falls back come from? On 3 June 1922 the mathematician Alexander Friedmann wrote from the Main Physics Observatory in Petrograd, as Saint Petersburg was then called, to the physicist Paul Ehrenfest in Leiden. Friedmann wrote that he had been working on "the question about the possible shape of the universe more general than the cylindrical world of Einstein". Einstein's "cylindrical world" was the physicist Albert Einstein's own model of the universe, which Einstein built from his own equations of gravity: a universe closed on itself and never changing in size. Among the answers, Friedmann wrote, "there appears also a world, the space of which possesses a curvature radius varying with time". The *curvature* of space is the way space as a whole can be bent. A curvature radius says how far you would have to travel before the bending of space showed, as the size of a ball says how far you must walk on the ball before you come round to where you began. In plain words, Friedmann had found that Einstein's equations al-

low a universe whose size changes with time. On 29 June 1922 the German journal *Zeitschrift für Physik* received Friedmann's paper, "On the Curvature of Space".

Einstein himself had pictured the universe as unchanging. Friedmann showed that Einstein's own equations allow worlds that grow and worlds that shrink. One of Friedmann's worlds grows from nothing to a greatest size and then shrinks back to nothing again. Friedmann gave that world a plain name: the periodic world. When the periodic world shrinks back to nothing, the shrinking is a recollapse, and Friedmann wrote that recollapse down seven years before Edwin Hubble's measurements of twenty-four galaxies, described in Chapter 1, showed that our own universe is expanding.

In Berlin, Einstein at first doubted Friedmann's result. Einstein wrote a short note saying that Friedmann's results about a changing world seemed suspicious to him. The same journal, *Zeitschrift für Physik*, received the note on 18 September 1922. Einstein withdrew his doubt in a second note, which the journal received on 31 May 1923. In the second note Einstein called Friedmann's results correct and clarifying. From then on, physicists counted a universe that changes its size with time as part of Einstein's theory of gravity.

Friedmann's picture uses two words, density and curvature. The *density* of the universe is the amount of matter and energy packed, on average, into each cubic meter of space. The curvature, as we have seen, is the way space as a whole is bent. Space can take one of three shapes. Space can be closed, the three-dimensional counterpart of the surface of a ball, so that a traveler going straight ahead long enough would come back to the start. Space can be open, bent the other way, like a saddle that keeps spreading. Or space can be *flat*: bent neither one way nor the other, so that lines that start out side by side stay side by side for ever, as in the geometry taught at school.

In worlds of Friedmann's kind that have no cosmological constant, the density and the curvature go together. For a given speed of expansion, the density fixes the curvature. When the density is below one dividing density, space is open, and the expansion goes on for ever. When the density is above the dividing density, the matter closes space, and the expansion slows, stops and falls back, like the ball thrown too gently. When the density is exactly the dividing density, space is flat, and the universe is like the ball thrown at the dividing speed, slowing for ever and never falling back. Some physicists held our universe to be closed. The physicist John Archibald Wheeler was one of those physicists. On the picture of a closed universe with no cosmological constant, our universe ends in a recollapse.

## Three Ways to Fall Back

How, then, could a recollapse come about? A recollapse could come about in three ways, and each of the three ways has its own champions among physicists.

First, there could be enough matter in the universe to stop the expansion. On Friedmann's picture, a universe that is dense enough is closed. The universe's own gravity then stops its expansion.

Second, the cosmological constant could change. Chapter 1 described the cosmological constant as an energy of empty space, the same in every cubic meter, which speeds the expansion up. If the energy of empty space later shrank, or turned from a push into a pull, the expansion could stop and turn around. Some physicists picture the dark energy as a drifting *field*, a quantity with a value at every point of space, as temperature has a value at every point of a room. On the picture of a drifting field, the field's energy falls with time and could even turn negative. Other physicists work in *string theory*, a proposed theory in which the smallest pieces of matter are tiny vibrating strings. String theorists picture empty space as able to settle into very many different conditions, called *states*, as a ball can come to rest in any one of many valleys. Each state of empty space has a

cosmological constant of its own. Some of the states' constants are positive and some negative. On the picture of string theory, a region of space could drop suddenly from the state our space is in into a lower state, inside a bubble that spreads outward. If the new state had a negative constant, the space inside the bubble would stop expanding and fall back.

Third, the end of an epoch could itself be a collapse of everything. Older pictures have a universe that repeats itself, and many newer pictures have a universe that bounces. In both kinds of picture the whole of space contracts to a smallest size before space expands again, so in both kinds of picture each end of an epoch is a recollapse of all of space at once.

## The First Way: Space Is Flat

Could there be enough matter to stop the expansion? Picture the expansion rate of Chapter 1, the rate at which the universe as a whole is growing, as set by a sum: in Einstein's equations the expansion rate is tied to that sum at every moment. The sum has three parts. The density part always adds to the sum, because matter and energy are never negative amounts. The curvature part subtracts from the sum, if space is closed. The part from the cosmological constant adds to the sum, if the constant is positive. In one sentence of words: the square of the expansion rate is the density part, minus the part from a closed curvature, plus the part from the constant. A recollapse needs the expansion rate to fall to zero, because a growing universe can begin to shrink only by first standing still, like the ball at the top of its flight. The square of the expansion rate is zero only when the part that subtracts equals the parts that add, so a recollapse needs the part that subtracts to catch up with the parts that add.

In this physics the curvature part of the sum is zero, and a ball shows the reason. A ball the size of the Earth looks flat from where you stand, while a ball the size of a marble is plainly curved. The size of a ball is a length, and a curvature of space is a length of the same kind: the size of

the ball that space as a whole would be curved like. Friedmann's curvature radius grows as space grows, in step with the stretching, as a circle drawn on a balloon grows when the balloon is blown up. When the curvature is measured in units that stretch along with space, the curvature does not change. In Einstein's equations the curvature, measured in stretching units, is set once, at the beginning of a universe's history, and carried unchanged ever after. The equations themselves do not fix the value of the curvature. So whatever sets the beginning of our epoch also sets the curvature of our epoch.

In this physics the beginning of our epoch carries over no length at all from anything that came before the beginning. I can give the reason now. No one in our epoch can compare anything with what came before the beginning of our epoch: no ruler of our epoch can ever be laid beside anything from before the beginning. This physics holds that a difference is a difference only when some comparison can, at some time, register that difference. So a length from before the beginning is no length of our epoch, because nothing in our epoch could ever be compared with that length. Part Two gives the full argument. Chapter 8 shows where an epoch begins, and Chapter 9 shows what passes into an epoch and what does not. In this physics the beginning of an epoch lies at the *Planck scale*: the scale of length, time and energy at which gravity and the *quantum* (the physics of the very small) meet on equal terms, so that neither gravity nor the quantum can be left out. At the Planck scale two descriptions of the world both reach their edge, the limit past which each description no longer holds. One description is the *smooth description of gravity*: Einstein's theory of gravity, which treats space and time as smooth. The other description is the *quantum description*: the physics of the very small, in which matter comes in separate steps. The beginning of an epoch holds only one length: the *Planck length*, the length of the Planck scale, far smaller than an atom. A curvature is a length, so the only ball the beginning could make space curve like is a ball of the Planck length, unimaginably small. A space closed like so small a ball would close up again, falling back together, almost at once. A space bent the other way on so small a length would

spread its matter apart so fast that no matter could ever clump. Stars, galaxies and black holes would form in neither kind of epoch. In this physics each epoch begins from the ends of the black holes of the epoch before, and every beginning is the same kind of beginning, recurring each time one epoch gives way to the next. If no black holes form in an epoch, no later epoch can begin from that epoch, so an epoch without black holes is not the kind of epoch that the cycle of epochs makes. Part Two describes the cycle of epochs in full. Chapter 1 has already said that our era is one of a sequence of eras. Our epoch has made stars, galaxies and black holes. So the space of our epoch is not curved like a ball of the Planck length, and the Planck length is the only length that the beginning of our epoch could have set. So the beginning sets no curvature at all, and the space of our epoch is flat, bent only by the tiny ripples, small bends from place to place, that the space of our epoch began with.

Now set the flatness of our epoch's space beside Friedmann's picture. Flat space is Friedmann's dividing case: the ball thrown at exactly the dividing speed. On Friedmann's picture, a universe is in the dividing case only if the universe's matter and its speed of expansion happen to match exactly. In this physics the match is not luck. The beginning sets no curvature, so the curvature part of the sum is zero whatever the amount of matter. More matter makes the density part larger, and the expansion rate larger with the sum, while the curvature part stays at zero. So matter adds to the sum and never bends space closed. Astronomers have measured the curvature of space on the largest scales, from the afterglow of the Big Bang and from the patterns in which galaxies are spread, and the astronomers find space flat.

Next, in this physics the cosmological constant is positive. I identify the cosmological constant with the part of empty space's energy that an observer inside the universe can take in by measurement. I work out how large the measured part is in *The View from Inside*, another book of this collection. The energy of empty space is a positive amount, and the part that a measurement takes in is a small fraction of that positive amount, so the

constant is positive. Two teams found the constant positive in the light of the supernovae they measured: the teams of Brian Schmidt and of Saul Perlmutter, in Chapter 1.

Now put the three parts together: the density part is never negative, the curvature part is zero, and the constant part is positive. So the sum is always larger than the constant part alone, and the expansion rate never falls to zero, for every amount of matter, because more matter only adds to a sum that is already positive. Gravity holds the expansion back, and gravity never stops the expansion. In the picture of the thrown ball, our epoch's expansion is a ball thrown from a world where the ball cannot come back.

In the far future the matter thins, and the expansion rate settles toward the rate that the constant alone sets, coming closer to that rate the longer the epoch lasts. What does fall back is smaller than the universe: a region denser than its surroundings and held together by its own gravity. The dense regions clump into stars, galaxies and black holes, as Chapter 1 described. The falling back of dense regions is a collapse of bound clumps inside the expanding space. The collapse of bound clumps comes up again below, in the section on the third way: a collapse of everything at an epoch's end.

## The Second Way: One Number for Our Whole Epoch

Could the cosmological constant drift, then, and someday turn into a pull? Think of a map with its scale printed in one corner: one inch to one mile. The scale belongs to the whole map at once. If a map's scale changed from one corner to the next, the map would not be one map.

The cosmological constant is like the scale of the map, for the one space and time of our epoch. The space and time of our epoch is the map, and the constant belongs to the whole of that space and time at once, as the scale belongs to the whole map. The form of Einstein's equations itself requires a strict account of energy and of *momentum*, the amount of mo-

tion: as the universe changes, energy and momentum move from place to place, and they are never made or lost. If the constant term changed from place to place, or from time to time, energy or momentum would be made or lost exactly where the term changed, and Einstein's equations allow no such break in the account. So within one geometry, meaning the one space and time of our epoch, the cosmological constant is one number: a theorem about Einstein's equations. So the constant cannot shrink, cannot grow, and cannot change its sign, because each of those would be a change in the constant.

Could the dark energy be the drifting field that some physicists picture? In this physics the dark energy is not a field. The dark energy is the part of the energy of empty space that a measurement takes in. The measured part enters Einstein's equations as their one constant term. Which measurement fixes the value of the constant? Chapter 1 showed that astronomers piece together every picture of the past from evidence we receive now: old light, the afterglow, instrument records. The measurement that fixes the constant is the measurement made now. Astronomers piece together one history from the present measurement, and that one history has the one measured value of the constant at every time in our epoch, after the present as well as before the present. In every epoch the same law sets the constant, and this physics gives the measured value of the constant to no epoch other than our own, so there is no drifting field behind the expansion whose energy could fall with time.

Could space drop into a lower state inside a bubble, as the string theorists picture? A drop needs somewhere to drop to: a lower state for empty space to fall into. In this physics every point of space carries a small hidden geometry. The hidden geometry determines which state empty space is in. The hidden geometry can change in only two ways, in its size and in its shape. The hidden geometry is held at one size and in one shape. So the hidden geometry has one held state, and no lower state of its own for a bubble to open into. Empty space also holds a second thing: the field that gives particles their masses. The field that gives particles their masses has an answer of its own, in Chapter 4. Chapter 4 also shows why

the hidden geometry has one shape and no second shape. The question of Chapter 4 is whether empty space could change its nature in any other way.

## The Third Way: The Collapse That Does Happen

Is the end of an epoch a collapse of everything? In this physics an epoch does end in a collapse. The collapse happens only inside the black holes of the epoch. The space between the black holes keeps expanding the whole time. The cosmological constant, which speeds the expansion, stays the same all the way to the end of the epoch, and the expansion that the constant speeds is what carries the galaxies off.

Each collapse belongs to its own black hole. Matter that falls into one black hole collapses inside that hole, on that hole's own clock, while the space outside that hole goes on expanding. No one on the back step will ever see an evening on which everything falls together. Some of the matter of an epoch never falls into a black hole at all: that matter is carried away alone, as Chapter 1 described, and Chapter 6 describes what becomes of that matter.

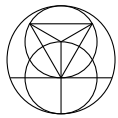
So the space of an epoch never contracts as a whole, because every collapse of an epoch happens inside a black hole, and the black holes are small regions within the space of the epoch. I walk through the rest of the story in Part Two of this book: how the end inside each black hole lies outside the time of the world around the hole, why the ends of all the black holes of an epoch are one end, and what follows. In Chapter 11 I set the pictures in which all of space shrinks and bounces beside the picture of this book.

## What This Means for You

From the back step, the faint smudges will not come back toward you. The space of our epoch is flat, and the cosmological constant, which speeds the expansion of our epoch, is positive and is one number for all of time in our epoch. Empty space has no second state to drop into, because the hidden geometry of space is held in one state. The galaxies beyond our own family of galaxies keep receding until they pass the cosmological horizon, as Chapter 1 described, and they never return. The collapse that ends our epoch happens in black holes, one by one, while the space between the black holes keeps on growing. Nothing in the sky above the back step will one day stop, turn, and rush back together.

> **Key idea.** A recollapse could come from enough matter, from a cosmological constant that changes, or from a collapse of all space at an epoch's end. In this physics the space of our epoch is flat, so matter cannot close the space of our epoch. The cosmological constant is positive, and Einstein's equations make the constant one number for all of time in our epoch. Empty space has no second state to drop into. The collapse that ends an epoch happens inside black holes, while the space between the black holes keeps expanding. Our epoch does not fall back. The question of this book is how the universe goes on, long after us, and the answer of this chapter is that the long emptying of Chapter 1 is the road our epoch takes, because our epoch does not fall back.

If the expansion never turns around, could the expansion instead grow strong enough to tear things apart?



Chapter 3

# Will the Expansion Tear Us Apart?

## What Holds Together

Will the expansion of the universe one day tear us apart? Stand on the back step again, on a clear night, and look up. In Chapter 1 you watched the faint smudges of other galaxies being carried out of sight by the expansion, one by one, and in Chapter 2 we found that the faint smudges never fall back. Yet the expansion carries away only some of what you can see and compare with from the step. The things that stay are held together by their own pull. The house beside you is held together, and so is the ground under the house, and so is the whole Earth. The Earth is held to the Sun. Overhead runs the pale band of the Milky Way, our own galaxy, and the Sun is held among the stars of the Milky Way. The Milky Way in turn is held in its small family of galaxies, the family that Chapter 1 called the Local Group. When a thing is held together by its own gravity, physicists call the thing *bound*, and an atom is bound as well, because the forces among the atom's particles hold the atom together. Is anything bound ever pulled apart by the expansion?

In this physics the answer is no: nothing that holds together is ever torn apart by the expansion. The expansion carries away the galaxies that are not bound to our own galaxy, as Chapter 1 told, while everything that is bound stays bound, as far as the expansion is concerned.

Some physicists have described a different end, in which the push of the expansion grows until the push tears everything apart, down to the atoms of your hand, and popular books call that end the Big Rip. A rip is a tearing apart by the expansion. We start with the account of the Big Rip in its authors' own terms, because their account shows exactly what a rip would need.

## A Phantom in the Dark

In August 1999 the physicist Robert Caldwell posted a paper with the title "A Phantom Menace?". In the summer of 1999 a film called *The Phantom Menace* was filling cinemas, and Caldwell's title plays on the title of the film. Caldwell asked what would follow if the dark energy, the energy of empty space that speeds up the expansion, were stranger than any kind of energy physicists usually allowed. Caldwell gave the strange kind of dark energy a name, the phantom, and he explained the name in a sentence: "A phantom is something which is apparent to the sight or other senses but has no corporeal existence", that is, something seen that has no body.

In February 2003 Caldwell worked out how the phantom would end the universe. He worked with the physicists Marc Kamionkowski and Nevin Weinberg of the California Institute of Technology in Pasadena. By then Caldwell was at Dartmouth College in Hanover, New Hampshire. The journal *Physical Review Letters* published the paper of Caldwell, Kamionkowski and Weinberg in August 2003. The title of the paper carried the words "Cosmic Doomsday". Caldwell, Kamionkowski and Weinberg found that phantom energy, Caldwell's strange kind of dark energy, grows denser without limit as the universe expands, so that the density of phantom energy reaches infinity at a definite time in the future. In their own words: "The phantom energy rips apart the Milky Way, solar system, Earth, and ultimately the molecules, atoms, nuclei, and nucleons of which we are composed, before the death of the Universe in a 'Big Rip'". A nuc-

leus is the tiny core of an atom, and nucleons are the particles that the core is made of. Nucleons are of two sorts: *protons*, which carry a positive electric charge, and *neutrons*, which carry none. The *electrons* are much lighter particles that circle around the nucleus.

Caldwell, Kamionkowski and Weinberg worked out the timetable of the rip for one example of phantom energy. In that example the end would come about twenty-two billion years from now. A cluster of galaxies is a swarm of hundreds or thousands of galaxies bound together. The clusters of galaxies would be stripped apart roughly a billion years before the end. The Milky Way would be torn apart about sixty million years before the end. A few months before the end, the Earth would be torn from the Sun. Molecules and then atoms would come apart about a ten-billion-billionth of a second before the end. The cores of the atoms would come apart in the instant that remained.

## What a Rip Needs

A balloon shows what a rip needs. The air inside a balloon pushes outward on the rubber, on every square inch of the rubber. Physicists call the push of the air on each small piece of the surface the air's *pressure*. The air also has a density. As Chapter 2 said, density is the amount of matter and energy packed, on average, into each cubic meter.

Every kind of stuff that fills the universe has a pressure and a density. Physicists call the rule that ties a substance's pressure to its density the substance's *equation of state*. For the stuff that fills the universe the rule is one number, the pressure divided by the density. The pressure divided by the density is the number that matters for the far future. For thin matter, such as dust and the galaxies themselves, the pressure is nearly nothing, so the number is zero. For light the number is one third. For the cosmological constant, the energy of empty space that you met in Chapter 1, the number is exactly minus one.

When the pressure of a substance is minus one times its density, the pressure is negative, and a negative pressure is a *tension*. Picture a rubber band stretched between your hands: the band pulls inward on your hands, and that inward pull is the band's tension. The cosmological constant has a tension like the band's, but the tension of the cosmological constant fills all of space. The band shows only what a tension is. In Einstein's theory of gravity, a tension that fills all of space makes the expansion of space speed up. So the effect of the constant on the expansion is a push outward, and the push of the constant is the same at every time of our epoch, because the constant never changes within our epoch.

The equation of state of a substance fixes what happens to the substance as space grows. The larger the number, the faster the substance thins as space expands. Matter thins as the volume of space grows, and light, whose number is larger, thins faster still. A substance whose number is exactly minus one does not thin at all. A substance whose number is below minus one grows denser as space expands. Physicists call a substance whose number is below minus one *phantom energy*: the substance is Caldwell's phantom.

Caldwell, Kamionkowski and Weinberg found the condition for a rip. A rip happens when the number of the dark energy lies below minus one, and only then. Caldwell, Kamionkowski and Weinberg gave their example of phantom energy a number of minus one and a half. For a number of exactly minus one, the three physicists found no rip in their own analysis: the outward push inside any fixed region stays the same for ever, so every system that is bound now stays bound. Whether the expansion can tear us apart therefore comes down to one number, the equation of state of the dark energy. What is the equation of state of the dark energy?

## One Number Through Our Whole Epoch

We can find the equation of state of the dark energy from two steps that Chapter 2 gave. First, in this physics the dark energy is the cosmological constant, which Chapter 2 identified with the part of the energy of empty space that a measurement made from inside the universe can take in. Second, a theorem about Einstein's equations shows that the constant is one number within one geometry. One geometry means the one space and time of our epoch. The measurement made now fixes that one number, once. We piece together the history of the universe from what reaches us now, and the history we piece together has the one measured value of the constant at every time of our epoch, after the present as well as before the present.

The dark energy is the constant, and the constant has one value at every time of our epoch, so the density of the dark energy never changes as the universe of our epoch expands. A density that never changes as space grows has an equation of state of exactly minus one, because minus one is the one number for which a substance does not thin. So the dark energy of our epoch has an equation of state of exactly minus one, now and at every later time of the epoch. A rip needs a number below minus one, and minus one is not below minus one. So the dark energy of this physics does not satisfy the condition for a rip. Caldwell, Kamionkowski and Weinberg set two cases side by side: a rip below minus one, and no rip at exactly minus one. Our epoch is the second case, the case with no rip.

Could something else in the world supply a phantom energy beside the constant? A phantom energy would need a field of its own: a quantity with a value at every point of space, spread through all of space, whose energy grows as space expands. Think of a full deck of playing cards. A full deck holds exactly fifty-two cards, because the four suits and the thirteen ranks are fixed. A fifty-third card would need a fifth suit or a fourteenth rank. The kinds of particle in this physics form a full deck, as the

cards do. Each kind of particle is told apart from every other kind by a few labels, such as its electric charge, by its family, and by the sort of field it is. Each label, family and sort of field plays the part of a suit or a rank. In this physics I derive which labels, families and sorts of field there can be, and every kind of particle that those labels, families and sorts of field allow is already in the list of kinds. A new kind of particle would need a new label, a fourth family or a fourth sort of field, as a fifty-third card would need a fifth suit, but the labels, families and sorts of field that I derive include none of those three additions. In that full list just one field fills all of space with a settled value. The one field is the field that gives particles their masses, which I name in Chapter 4. Physicists have calculated the history of the early universe. The physicists report that the field that gives particles their masses took its present value long before the expansion began to speed up, and from then on the energy of that field has been constant. So no matter and no field in the world carries an energy that grows as space expands. No field whose energy changes drives the speeding up of the expansion.

The constant, one steady number, also sets the pace of the expansion. The rate of the expansion settles toward one steady pace and comes closer to that pace for ever, because the constant is positive and unchanging. Every observer has a horizon: the boundary beyond which no event can ever send the observer a signal. Each observer's horizon grows toward one fixed size. A rip needs the opposite: a pace of expansion that becomes infinite at a set time, and a horizon that closes in.

## A Steady Wind on the Step

Picture yourself on the back step in a breeze. A steady breeze, the same every minute, makes you lean a little. You find your balance once, and then you stand there all night. You will in the end be knocked off the step only by a wind that keeps rising without limit. The cosmological con-

stant is the steady breeze, and each bound thing is like you, keeping your balance on the step. The phantom of Caldwell, Kamionkowski and Weinberg is the wind that keeps rising.

Everything that is bound now is bound in a world that already contains the constant at its present value. The Earth goes round the Sun, and the Sun goes round the center of the Milky Way, with the small outward push of the constant already acting on the Earth and on the Sun. The constant has its present value at every later time of our epoch, so the push of the constant is the same at every later time as the push is now. The push of the constant is one part of the balance that holds any bound thing together, and the push shifts the balance once, by a fixed amount, and never by a growing amount.

Each bound thing is held together by a pull. How large is the constant's fixed push, set beside that pull? I give three answers below, worked out by arithmetic from the measured value of the constant and the measured masses and sizes of bound things. The Milky Way sits inside its halo, a roughly round cloud of matter that reaches far beyond the stars. Most of the matter in the halo is unseen. At the outer edge of the halo of the Milky Way, the push is about seven thousandths of the pull. For the Earth in its orbit about the Sun, the push is about eight parts in a hundred thousand billion billion of the pull. The electron in a hydrogen atom is held by the electric pull of the atom's core, and for the electron the push is a fraction of the pull whose first digit that is not zero comes sixty-nine places after the decimal point. For the halo, for the Earth and for the electron, the fraction is the same tomorrow, in a billion years, and in a trillion years. The push never overtakes the pull in any of the three cases, because each push stays the same fraction of its pull and never grows.

## Binding Lives Where the Matter Is

A second picture shows why a constant never tears anything apart. Picture a loaf of raisin bread rising in the oven. As the dough swells, every raisin moves away from every other raisin, but no raisin swells, because each raisin holds itself together. The expansion is like the dough between the raisins, and each bound thing is like a raisin.

The picture of the raisin bread matches what gravity and the cosmological constant each do. Gravity's hold on a thing is local: gravity acts where the matter is, in proportion to how much matter there is, and gravity draws the parts of a galaxy, a star or a planet toward one another. Within our epoch, the cosmological constant is the same at every place and every time. The constant gathers at no place, so the constant has no way to build up against the hold of any one bound thing. The only effect of the constant is on the course of the universe as a whole, where the constant widens every great distance alike. I put the point in one sentence in my book *The Weight of Possibility*, another book of this collection, speaking of an epoch like ours: "The cosmological constant is the same at every place and at every time, and it increases the distance between every pair of distant places".

An atom or a molecule is held together by the forces among its particles. Gravity plays almost no part in holding an atom or a molecule together. In this physics a kind of particle has the same properties wherever and whenever a particle of that kind is found. For us, who live in our epoch, a kind of particle therefore has the same properties at every place and every time of our epoch. So an atom is made of the same particles, held to one another by the same forces, at every later time of our epoch. The forms of matter (atoms, stars and bodies) stay fixed for as long as the hidden geometry of empty space that holds those forms lasts, and Chapter 4 says how the hidden geometry holds the forms of matter. So

while the forms of matter last, an atom keeps its size, because the balance that sets that size stays the same. As far as the expansion is concerned, the atoms of your hand will be the same size in a trillion years as tonight.

## How Bound Things Do End

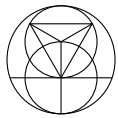
In this physics, bound things do end. Within each observer's horizon, as Chapter 1 told, gravity gathers matter into clumps. Every bound structure has two possible ends: a bound structure ends inside a black hole, or the structure is carried away alone, carried by the expansion beyond the reach of all other matter. Chapters 5 and 6 follow both ends. Neither end is a tearing apart by the expansion.

## What This Means for You

Look from the back step again: the bound part of the world that you see and compare with stays together. The house and the ground will never be pulled apart by the expansion. Neither will the Earth be pulled from the Sun, nor the Sun from the Milky Way, nor the Milky Way from its family of galaxies. The atoms of your hand hold their size against the expansion for as long as there are atoms. The expansion carries off only what is not bound, the faint smudges of Chapter 1, while to everything that is bound the expansion adds one small, steady push that never grows. The bound things of the sky have two ends, inside a black hole or carried away alone, and the next chapters follow those two ends.

**Key idea.** Caldwell, Kamionkowski and Weinberg showed in 2003 that a rip would need a dark energy that grows denser as space expands: a dark energy with an equation of state below minus one. In this physics the dark energy is the cosmological constant, one number, fixed once and the same at every time of our epoch. The equation of state of the constant is exactly minus one, and the condition for a rip is not satisfied. A constant push is already part of the balance that holds a galaxy, a planet or an atom, and the constant push never grows, so nothing bound is ever torn apart by the expansion. So in the far future the bound things of the sky come only to their own two ends: inside a black hole, or carried away alone.

If the expansion never tears apart what is bound, could empty space itself change into something else?



Chapter 4

# Could Empty Space Change Its Nature?

## The Sky Overnight

Look up from the back step once more. Could empty space itself change its nature overnight, into something else? You can see and compare with many things from the back step, and every one of them sits in empty space: the stars, the dark between the stars, and the light that crosses the dark to reach you. Chapter 3 showed that the expansion never tears apart what is bound. Some physicists have asked a stranger question. Could the empty space we live in be only resting for a while, so that one day it gives way, everywhere, to a different kind of empty space with different laws for matter? If our empty space gave way, the world you compare with would change underneath everything in that world.

Physicists call the settled state of empty space the *vacuum*: what empty space is like when nothing at all is put into it. In this physics the vacuum has two settled features. The first feature is the held shape of the small hidden geometry that every point of space carries, which Chapter 2 introduced. The second feature is the settled value of one field that fills all of space. The hidden geometry has one held shape and no second shape to fall into. The hidden geometry is held in its shape while one condition is met: the large world of space and time must be there around the hidden geometry, with things in that world to compare against. The hold on the

shape ends only where the condition fails. The condition fails in two places: at the end of a black hole's interior, and for a body carried away alone (a body carried by the expansion beyond the reach of all other matter). Whether the settled field could change has its own answer, and I give that answer after the answer for the hidden geometry. I begin this chapter with the scene in which a physicist set out the question of whether empty space could give way.

## Bubbles in a Superheated Liquid

On 24 January 1977 the journal *Physical Review* received a paper from the physicist Sidney Coleman. Coleman was at the Lyman Laboratory of Physics at Harvard University in Cambridge, Massachusetts. The title of Coleman's paper was "Fate of the false vacuum". A *false vacuum* is a settled state of empty space that holds for now but is not the lowest state empty space could have. Coleman asked his readers to picture a *superheated liquid*: a liquid heated past its boiling point and kept from boiling. Coleman wrote of the superheated liquid: "Thermodynamic fluctuations are continually causing bubbles of the vapor-phase to materialize in the fluid phase". In plain words, the heat jostles the liquid, and the jostling keeps making tiny bubbles of steam, but most of the bubbles are too small to grow, and each small bubble shrinks to nothing. Coleman went on: "However, once in a while, a bubble is formed large enough so that it is energetically favorable for the bubble to grow". Then, in Coleman's words, "the bubble expands until it converts the available fluid to vapor".

Coleman's point was that empty space itself might be like the superheated liquid. Empty space might be held in a state that is not its lowest, waiting for one bubble. Coleman put the point in one sentence: "An identical picture describes the decay of the false vacuum", he wrote, "with quantum fluctuations replacing thermodynamic ones". In empty space the bubbles would come from the restless chance of quantum physics, and not from heat.

Three years later Coleman added gravity to the picture, together with the physicist Frank De Luccia. Coleman was then at the Stanford Linear Accelerator Center in California, and De Luccia was at the Institute for Advanced Study in Princeton. Their paper reached *Physical Review* on 4 March 1980. Coleman and De Luccia found that when a bubble leads from a space like ours into an empty space whose energy is below zero, the space inside the bubble collapses under its own gravity in "microseconds or less". Coleman and De Luccia wrote near the end of their paper: "The possibility that we are living in a false vacuum has never been a cheering one to contemplate. Vacuum decay is the ultimate ecological catastrophe; in a new vacuum there are new constants of nature; after vacuum decay, not only is life as we know it impossible, so is chemistry as we know it. However, one could always draw stoic comfort from the possibility that perhaps in the course of time the new vacuum would sustain, if not life as we know it, at least some structures capable of knowing joy. This possibility has now been eliminated".

## Valleys and Bubbles

A picture helps to follow Coleman's question of whether empty space could give way: picture a hilly country with many valleys. Set a ball at the bottom of one valley. Nudge the ball, and the ball rolls a little way up the slope, rolls back, and settles where it was. The bottom of the valley holds the ball.

A vacuum is like the bottom of a valley that holds a ball. A vacuum is a settled state, held by the laws of motion, so after a small push the state returns to where it was, as the nudged ball rolls back to the bottom of its valley. If one valley is the lowest in the whole country, the bottom of that valley is the *true vacuum*. When a valley holds the ball but is not the lowest, the valley is a false vacuum, and somewhere beyond the ridge of the false vacuum lies a lower valley.

In everyday life a ball in a valley stays in the valley unless something lifts the ball over the ridge. In quantum physics the ball need not be lifted, because a ball held in a valley can pass through the ridge into a lower valley without ever climbing over the top. Physicists call the passing of the ball through the ridge *tunneling*. For a whole world held in a false vacuum, the tunneling begins in one small region. A bubble of the lower vacuum forms in the small region. If the bubble is large enough, it grows, as a bubble of steam grows in Coleman's superheated liquid.

The decay of a false vacuum always needs one thing. For tunneling to happen, there must be a second valley, lower than the first, for the bubble to lead to. So the question of this chapter becomes plain. In this physics, does empty space have a second, lower valley?

## The Six Small Dimensions

Start with the small hidden geometry that Chapter 2 introduced. Picture a garden hose lying across a lawn, seen from far away. From far away the hose looks like a line, with only one direction along the line, but come close and you find a second direction, which curls round the hose and comes back to where it started. The small round direction is there at every point along the hose, too small to see from far off.

In this physics, space is like the hose, but space has more small directions than the hose. Every point of space carries six further directions besides the three directions of space and the one direction of time. The six further directions are curled up far smaller than the core of an atom, about the size of the Planck length of Chapter 2. The six further directions are the *six small dimensions*, which physicists also call the *internal space*. In all there are ten dimensions: the six small dimensions, the three dimensions of space and the one dimension of time.

Why should six curled directions make any difference to the matter around you? Read in another way, the six small dimensions are the space of all the states that a particle of matter can be in, as a chessboard is the set

of all the squares on which a chess piece can stand. The squares are like the states, and the piece is like the particle. So the shape of the six small dimensions sets which kinds of particle there are, and how those kinds can join into atoms and bodies. While the shape of the six small dimensions is held, the forms of matter stay fixed: the atoms, stars and bodies of our epoch.

The six small dimensions have a shape made of two simple curved shapes side by side. One is a sphere of two dimensions, and the other is a larger curved shape of four dimensions. The shape follows from a derivation in this physics, and it is the only shape that satisfies the conditions that the derivation sets. No one picks the shape from a list of possible shapes.

How many ways are there to set the shape of the six small dimensions? A perfect ball has no special spot: every point of the ball's surface is like every other point. Once you know how big a perfect ball is, you know every distance on the ball, but if you stretch the ball toward the shape of an egg, you give the ball ends, and ends are special spots. I take each of the two shapes of the six small dimensions to be like the perfect ball: the same at every point of itself. My reason is that each of the two shapes is part of the arena in which things are compared, the whole setting of every comparison. The arena cannot itself single out one of its own points, because nothing found in any comparison would mark that point out. If each of the two shapes is the same at every point of itself, a theorem of geometry shows that the six small dimensions have exactly two settings: the overall size of the six small dimensions, and the ratio of the radii of the two shapes.

A single step fixes both settings: I take every direction of the six small dimensions to bend by one and the same amount. The amount is the bending at the Planck scale. Chapter 2 introduced the Planck scale, at which two descriptions in physics both reach the edge of the range in which each holds. The two descriptions are Einstein's theory of gravity, which treats space and time as smooth, and the physics of the very small. The bending at the Planck scale fixes the radius of the sphere at one

Planck length, and the radius of the larger shape at the square root of six Planck lengths, about two and a half Planck lengths. So both settings are fixed, and nothing in the six small dimensions is left free to vary. The step fixes the size and shape alike at every point of space. The step fixes the size of the six small dimensions in Planck lengths, the unit of length that the strength of gravity sets. Physicists take the strength of gravity from measurement, and the strength of gravity has one value throughout our epoch.

What keeps the six small dimensions at their one size and shape? In this physics the six small dimensions are dimensions of possibility: they are the range of what is possible, and each outcome of a comparison is one selection from that range. Nothing travels through the six small dimensions. Each time anyone makes a comparison, the one who compares finds something in some respect, within some setting. What is found in a comparison is its content. The setting in which the content is found is the context of the comparison, and Chapter 6 uses both names. In this physics every content has a context: there is no content without a context. The rule that every content has a context is part of the third axiom, which is one of the starting principles of this physics and which Chapter 8 sets out in full. The six small dimensions are part of the context of every outcome, so they cannot shrink to nothing.

Quantum physics gives a second reason. Quantum physics allows nothing to be held at one exact value with no spread at all, and for that reason the electron of an atom never falls into the atom's core. A size held at exactly zero would be a value with no spread at all, so the six small dimensions have a floor, a least size below which they cannot be pressed. The six small dimensions are held at their one size and shape for as long as the large world of space and time is there around them, with things in that world to compare against. The six small dimensions have one space (the one shape that the derivation allows), two settings, and one held size and shape, so they have one vacuum.

## No Threads, No Landscape

Chapter 2 introduced string theory, a proposed theory in which the smallest pieces of matter are tiny vibrating strings. String theory also curls six dimensions small. In string theory, Coleman's question of whether empty space could give way arises in its sharpest form. In string theory the six small dimensions are curled into shapes with many loops, as a ring has a hole. Certain fields can be threaded through the loops. Each loop then has a whole number, which counts how many times a field is threaded through the loop, and each allowed choice of the whole numbers produces a different valley, that is, a different vacuum. Physicists estimate the number of valleys at ten to the five hundred, a one followed by five hundred zeros, or more. Each valley has its own energy of empty space and its own physics, and physicists call the whole many-valleyed country the *landscape*.

In this physics the law of gravity follows from the geometry of all ten dimensions alone, the six small ones together with space and time. A field threaded through the six small dimensions would add two things that this physics does not have. First, the threaded field would add an energy of its own to the energy of empty space, and so the added energy would change the result of this physics for how much of the universe is matter. Second, the strength of the threaded field would be a second number beside the strength of gravity, while in the part of this physics that describes gravity the strength of gravity is the one measured strength. So in this physics no field is threaded through the six small dimensions. Picture a ring whose hole is empty: no thread is wound through the hole, so there is nothing to count. When no field is threaded through any loop of the six small dimensions, there is no whole number to choose. So this physics has no landscape: the six small dimensions have one valley, and no second valley for a bubble to tunnel to.

## Where the Hold Ends

The hold on the six small dimensions does end, and it ends in one way: where the condition that holds them fails. The six small dimensions are held while the large world of space and time is there around them, with things to compare against. The condition is met in every part of the world that you can see from the back step and compare with. The condition fails in two places. The first place is the end of a black hole's interior. The second place is a body carried away alone, which the expansion has carried beyond the reach of all other matter. A body carried away alone has nothing within its reach to compare against. Chapter 6 describes what a body carried away alone loses, and what anyone on the body loses.

A black hole has a horizon: the boundary of the region from which nothing can return. Inside the horizon, the direction toward the center is the direction of time, so every path inside the horizon leads forward to an end. On the clock of a body that falls in, the end comes after a finite time, as a limit: for a black hole of the Sun's mass, the end comes at most about fifteen millionths of a second after the body crosses the horizon. The end lies at no moment of the outside world's time. So at the end of a black hole's interior the outside world has no moment at which to be there around the six small dimensions, and so nothing is there to compare against. The condition that holds the six small dimensions therefore fails at the end of a black hole's interior. The ends of all black hole interiors are one end, as Chapter 8 shows. I call the one end of the interiors of all black holes the *turn*. The turn is a limit, approached from the side of the old epoch and from the side of the next, and reached from neither. The turn is not an event that a history goes through. The next epoch begins from the turn. Chapter 8 describes the turn in full.

The turn is not a bubble of a lower vacuum, because on the far side of the turn there is no second held shape for the six small dimensions to fall into. In the next epoch the law that holds in our epoch holds again. The

six small dimensions re-form with the same shape as in our epoch, and at the same size as in our epoch, counted in Planck lengths, because the single step that fixes the shape and the size in our epoch fixes them again in the next epoch. I count the size in Planck lengths for a reason. A length can be known only by laying the length beside another length, but no one ever lays a ruler of our epoch beside a ruler of the next epoch, because no comparison is made across the turn. So in this physics the six small dimensions of another epoch have no size in our meters, but in every epoch the six small dimensions have the same size, counted in that epoch's own Planck lengths. Chapter 9 describes each epoch's ruler, its own Planck length.

## Coleman's Question, Answered for the Six

Coleman showed how a world held in a vacuum that is not the lowest could give way, by one bubble that grows. Coleman and De Luccia showed what gravity does to a bubble that grows, and they found the collapse inside the bubble that ended their hope of structures capable of knowing joy. Both results depend on one condition: there must be a second, lower valley for the bubble to lead to. In this physics the six small dimensions have one space, two settings and one held size and shape, and no threaded field makes more valleys. So the six small dimensions have one vacuum, and no second vacuum for a bubble to lead to. The hold on the six small dimensions ends only where the condition of the hold fails, at the end of a black hole's interior and for a body carried away alone. Where the condition fails, there is no lower valley for the six small dimensions to fall into.

## The Higgs Field

The vacuum of this physics has a second settled feature, a field, besides the held shape of the six small dimensions. Chapter 2 said that a field is a quantity with a value at every point of space, as temperature has a value at every point of a room. The *Higgs field* fills all of space, and it has settled at a value that is not zero, the same everywhere. By that settled value the Higgs field gives many of the elementary particles their masses. The elementary particles are the smallest pieces of matter, such as the electron. The settled value of the Higgs field is its vacuum. The Higgs field is a field on space and time, and not a change in the six small dimensions. The six small dimensions are unchanged by the Higgs field.

Picture the bottom of a wine bottle, which has a raised bump in the middle and a round trough all about the bump. Let the height of the glass stand for the energy of the Higgs field, and the distance from the center stand for the size of the field's value. At the center, where the Higgs field is zero, the energy is raised, as the bump is raised. The Higgs field has settled in the trough that runs around the bump.

In this physics I derive the curve of the energy of the Higgs field. The curve has two parts. One part pulls the energy down as the square of the size of the field's value, and the other part, which is positive, pushes the energy up as the fourth power of that size. When a curve is made of a square part that pulls down and a fourth-power part that pushes up, the curve has one lowest place, and for the curve of the energy of the Higgs field the lowest place is the trough of the present vacuum. At the center the energy is higher than in the trough, and beyond the trough the energy rises without limit. Every point of the trough is equally low, and the trough is one unbroken ring, so the trough is one vacuum and not many.

Could the Higgs field slip away from the trough in some other direction? The Higgs field could slip away only if there were another field of its kind to move in. In this physics a field of the Higgs field's kind can exist

only where a force crosses from one member of a matched pair of particles to the other. The *weak force* acts in some kinds of radioactive decay. *Quarks* are the smaller particles of which protons and neutrons are each made, three to each. The weak force crosses from one member of a matched pair to the other: it turns an up quark into a down quark, for instance. In the structure of particles and forces that I derive in this physics, the weak force crosses one of the places where a field of the Higgs field's kind could exist, and no force crosses any other of those places. So there is one place for a field of the Higgs field's kind, and one such field. The Higgs field therefore has one direction to vary in, its size, and no other direction in which a lower valley could lie. This physics also has the principle that every way of varying has a least state, so every fall has a limit, and so the energy of the Higgs field has a floor.

In quantum physics the strength of a force changes slowly with the energy at which the strength is measured. So the strength of a force is not one fixed number. The Higgs field acts on itself with a strength that also changes with the energy. The strength of the Higgs field on itself sets the size of the fourth-power part of the curve. In this physics I work out the strength of the Higgs field on itself at the energies of the weak force. The energies of the weak force are the energies at which physicists measure the *Higgs boson*, a small ripple of the Higgs field.

The *Standard Model* is physics' established account of the particles and of every force but gravity. Physicists have followed the Standard Model out to far higher energies. In 2013 the physicist Dario Buttazzo and his colleagues reported a calculation that follows the Standard Model out to far higher energies. Buttazzo and his colleagues used the measured masses of the Higgs boson and of the top quark, which is the heaviest known elementary particle. The mass of the Higgs boson sets the strength of the Higgs field on itself at the energies where the Higgs boson is measured. The top quark feels the Higgs field most strongly of all the particles, and the top quark does most to change the strength of the Higgs field on itself as the energy rises. In the calculation of Buttazzo and his colleagues, the strength falls to small or negative values at very high energies. Where the

strength is negative, the curve of the energy turns down again far out beyond the trough, and so the curve has a region far out beyond the trough that is lower than the present state. In the calculation of Buttazzo and his colleagues the present state of the Higgs field is held, and could pass by tunneling to the far region, but the present state lasts far beyond the age of the universe. When a held state could tunnel to a lower state but lasts far beyond the age of the universe, physicists call the state *metastable*.

For the Higgs field, the answer of this chapter is that the energy of the Higgs field has a floor in this physics, and in the two-part curve that I derive, the floor is the present state. In this physics I do not follow the strength of the Higgs field on itself out to very high energies. The standard calculation of Buttazzo and his colleagues does follow the strength out to very high energies. In the standard calculation the present state lasts far beyond the age of the universe.

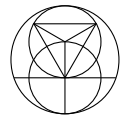
## What This Means for You

The sky over the back step will not change its nature overnight. The empty space between the stars carries the six small dimensions at every place, held at one shape and one size for as long as the large world of space and time is there around the six small dimensions. The six small dimensions keep one held shape, and that shape fixes the forms that matter can take, so the forms of the matter of your body, and of the matter of the stars you look at, stay fixed. The six small dimensions have no other kind of space to become, so no bubble of another kind of space can open in them. The hold on the six small dimensions ends only where its condition fails, at the end of a black hole's interior or for a body carried away alone, and in the next epoch the same six small dimensions re-form. In this physics the energy of the Higgs field has a floor. In the two-part curve that I derive, the floor is the present state. In this physics I do not follow the

strength of the Higgs field on itself out to very high energies, but in the standard calculation, which does follow the strength that far, the present state lasts far beyond the age of the universe.

> **Key idea.** A vacuum is the settled state of empty space, and a vacuum can decay only if a second, lower vacuum exists for the first vacuum to tunnel into. The six small dimensions of this physics have one space, two settings and one held size and shape, and no threaded field. So in our epoch the six small dimensions have the only held shape that they can have. The hold ends only where its condition fails: at the end of a black hole's interior, or for a body carried away alone. The hold matters for the far future, because the shape of the six small dimensions fixes the forms of matter, and the forms of matter last until the hold ends.

If empty space keeps its nature through our epoch, what becomes of the matter in empty space?



Chapter 5

# What Becomes of the Stars and Their Ashes?

## The Stars over the Step

Stand on the back step again on a clear night. This time, look at the stars of our own galaxy rather than at the faint smudges of other galaxies. What becomes of the stars you see, and of what each star leaves behind when the star goes out? Every star you see is burning a fuel, and every fuel runs out. So over the ages the stars go out one by one. Each star leaves something behind when it goes out. This chapter calls what is left the star's ash, or the star's remnant.

The ash of a star is one of three kinds. The kind of ash depends on how heavy the star was. A star like the Sun leaves a *white dwarf*: the cooling remnant of a star that has burned its fuel, about as heavy as the Sun and about as large as the Earth. A much heavier star leaves a *neutron star*: a ball more massive than the Sun, some twenty-five kilometers across, packed as tightly as an atom's nucleus. The nucleus is the tiny, heavy center of an atom. A neutron star is made mostly of *neutrons*, the particles without electric charge that sit in the nucleus of every atom except the simplest. A heavier star still leaves a black hole, the region from which nothing climbs back out, not even light.

In short, the ashes of the stars last. White dwarfs and neutron stars hold themselves up without any heat. The particles of white dwarfs and neutron stars do not break up into lighter particles. So each white dwarf and each neutron star cools and keeps its matter until its path ends in one of two ways: inside a black hole, or carried away alone, which means carried by the expansion of the universe beyond the reach of all other matter (Chapter 1). The black holes themselves fade last of all, far later still than every other ash. So the sky over the step darkens, while the matter that made the stars of that sky never wastes away.

## A Star That Has Burned Its Fuel

A star keeps its size by a balance between two pushes: gravity pulls the matter of the star inward, and the heat of the nuclear burning in the core of the star pushes the matter outward. When the fuel is spent, the heat no longer comes, and gravity squeezes what is left of the star.

Sirius, the brightest star in our night sky, has a white dwarf for a companion, so close to Sirius in the sky that only a large telescope can pick the companion out of the glare. Astronomers call the companion Sirius B, and they have weighed Sirius B from the orbit that the two stars trace around each other every fifty years: Sirius B has about the mass of the Sun. Astronomers have also measured the size of Sirius B. The light of Sirius B is stretched as the light climbs out of the pull of Sirius B, and from the stretching astronomers find a radius of about 5,600 kilometers, smaller than the Earth. A teaspoon of Sirius B would weigh about fourteen tonnes.

A much heavier star ends more violently. The core of the heavier star collapses in less than a second, and the star explodes. The core left behind is a neutron star, or a black hole if the core is heavier still. A teaspoon of neutron star matter would weigh about two billion tonnes.

So the night sky of the far future holds three kinds of ash: white dwarfs, neutron stars and black holes. Chapter 1 has already described the black holes and their slow glow. The white dwarfs and the neutron stars leave us a question of their own: when no heat is left in a white dwarf or a neutron star, what holds the star up against gravity?

## A Voyage in 1930

On the last day of July 1930, Subrahmanyan Chandrasekhar, a young man of nineteen, sailed from Bombay for England. Chandrasekhar had finished his degree in physics at the Presidency College in June 1930. A scholarship from the Government of India was taking him to graduate study at Cambridge. He went by steamer to Venice and on to London by rail, and he spent the voyage working.

On the voyage Chandrasekhar worked on the question of what holds up a white dwarf that has no heat left. Four years earlier, the Cambridge physicist Ralph Fowler had shown what holds up a white dwarf. Fowler's answer comes from a rule about *electrons*, the light particles that circle the nucleus of every atom. The rule is that no two electrons can be in the same state. Two electrons cannot share both the same place and the same motion. The rule is called *exclusion*. Crowded electrons must take states one to a state, from the lowest up. The electrons fill their states as people fill a theater from the front, one person to a seat. In the picture, each seat stands for one state, and the seats nearest the front stand for the states of lowest energy. Squeeze the crowd of electrons into a smaller room, and the seats near the front are gone, so the crowd must sit further back, in dearer seats, and the energy of the crowd rises. When the energy of a crowd rises as the crowd is squeezed, the crowd pushes back against whatever squeezes the crowd, and the push of the crowd is called *degeneracy pressure*. Degeneracy pressure is the pressure that a crowd of electrons exerts because, by exclusion, the electrons cannot all settle into the lowest states. Degeneracy pressure needs no heat at all.

On board, Chandrasekhar saw a point that Fowler had left out. In a heavier white dwarf the electrons are squeezed harder. The fastest of the electrons move at nearly the speed of light. Chandrasekhar recalled in a 1977 interview: "it wasn't very difficult to see it with increasing mass the velocities were approaching the speed of light". Near the speed of light, the push of the electrons grows more slowly with the squeezing than the push of low-speed electrons grows, so as the star gets heavier, the squeeze of gravity catches up with the push of the electrons. Above one particular mass, there is no size at which the star can hold itself up. Chandrasekhar had with him a book by Arthur Eddington on simple model stars, which are stars worked out on paper from a few simple assumptions, and with Eddington's book, Chandrasekhar said, "it was very easy to compute what the limiting mass was". In 1931 Chandrasekhar published in *The Astrophysical Journal* the formula that was, in his words, "the one which I derived on board the steamer". Astronomers now call the greatest mass a white dwarf can have the *Chandrasekhar mass*. The Chandrasekhar mass is about 1.4 times the mass of the Sun, and every white dwarf that astronomers have weighed lies below the Chandrasekhar mass.

## Held Up Without Heat

Fowler and Chandrasekhar give us the first step of the answer to what holds up a cold remnant. A white dwarf is held up by the exclusion of its electrons, and exclusion is present at the lowest temperature there is, so a white dwarf that loses its heat keeps its size.

A neutron star is held up in the same way as a white dwarf, with one push added. The neutrons of a neutron star obey exclusion too, so they fill their states from the lowest up and press outward, like a white dwarf's electrons. The added push comes from the force between nuclear particles. Where the star presses its neutrons closer together than neutrons sit in a nucleus, the force between the particles of the nucleus adds a

push of its own, because the energy of so many neutrons packed so close grows as the neutrons are squeezed. Both pushes come from squeezing, and neither push comes from heat.

Now let a white dwarf or a neutron star cool. A body that shines into colder surroundings loses heat, because heat always passes from the hotter body to the colder one. Over the long emptying of the sky, the radiation around the remnant thins and grows ever colder, so the remnant keeps losing heat. The pressures that hold the remnant up do not depend on the temperature of the remnant, so the cold remnant keeps its size. When a white dwarf has cooled until it no longer glows, the cold star is called a *black dwarf*: a dark, solid ball about the size of the Earth, still holding the mass of a star.

So we now have the first half of this chapter's answer. White dwarfs and neutron stars hold themselves up by squeezing, not by heat, so a remnant that cools stays held up as well as when it was hot. What remains to ask is whether the matter itself lasts.

## Does the Proton Last?

Every atom has a nucleus of protons and neutrons at its center. A *proton* is the particle of the nucleus that carries a positive electric charge. The nucleus of the simplest atom, hydrogen, is a single proton. Protons and neutrons are each made of three smaller particles called *quarks*, and particles made of three quarks are called *baryons*. Every kind of particle has a twin with the opposite electric charge, called its *antiparticle*. The *baryon number* of a body is the body's count of baryons, with each antiparticle of a baryon counted as minus one.

When physicists say that a particle *decays*, they mean that the particle breaks up into lighter particles. For half a century many physicists have expected the proton to decay, because of a family of theories called *grand unified theories*. The grand unified theories join three forces into one. The three forces are the *strong force*, which binds quarks together, the weak

force and the electric force. The weak force is the force at work in some kinds of radioactive decay (Chapter 4). Every grand unified theory includes particles that can turn a quark into a *lepton*: a member of the electron's family of light particles. In grand unified theories, a proton breaks up into lighter particles over an immensely long time, and its baryon number is lost. If protons decay, every white dwarf and neutron star slowly wastes away.

Physicists have looked for the decay of the proton. At midnight on the first of April 1996, the physicists of the experiment Super-Kamiokande began their watch for the decay. Super-Kamiokande lies in a mine near the town of Kamioka in Japan: a tank holding fifty thousand tonnes of pure water, with walls lined with more than eleven thousand detectors of faint light. Physicists had built an earlier experiment in the same mine, Kamiokande, to search for exactly the decay of the proton. A tank of fifty thousand tonnes of water holds a vast number of protons, so even a lifetime far longer than the age of the universe would show itself as an occasional flash, because among so many protons a few would decay during the watch. The Super-Kamiokande collaboration is the team of physicists who run the experiment. In 2020 the collaboration reported on the whole of the watch. The team had seen no proton break into a positron (the electron's antiparticle) and a light particle called a pion, so the lifetime of the proton for the decay into a positron and a pion is above twenty-four million billion billion billion years.

This physics gives the reason that no decay has been seen. The forces among the particles come from three separate symmetries: three ways of relabelling the particles that leave the laws of physics unchanged. One symmetry is for *color*, the charge of the strong force, which quarks carry. A second symmetry is for the *weak charge*, the label on which the weak force acts. The third symmetry is for electric charge. The three symmetries stand side by side, each keeping its own identity, as a book and a cup do on a table. Mix blue and yellow paint and you get green, a blend from which neither of the two paints can be taken back out. In the picture, the book and the cup stand for the three symmetries kept apart, and the green

paint stands for the blend of three forces into one that the grand unified theories make. The forces of this physics are like the book and the cup, not like a pot of green paint.

Each force is carried by particles of its own, called its carriers. Each carrier belongs to one symmetry only. So no carrier joins color to the weak charge. A quark carries color, and a lepton carries none. So turning a quark into a lepton would need a carrier that acts on both color and weak charge, and no such carrier exists. Therefore no change turns a quark into a lepton, and no process changes the baryon number. The proton is the lightest particle made of three quarks, as measured, so it has nothing lighter to become while keeping its baryon count. The proton lasts.

The rest of the matter of a remnant lasts too. The electron is the lightest particle that carries electric charge, as measured, and charge is never lost, so the electron has nothing to decay into. A neutron on its own decays in about fifteen minutes into a proton, an electron and a light neutral particle. White dwarfs are made of nuclei of carbon and oxygen, with helium in some white dwarfs, and inside those nuclei a neutron cannot decay. The decay of the neutron would leave behind a heavier nucleus than the nucleus the decay started from, and a change happens only if what comes out weighs less than what went in. Inside a neutron star a neutron cannot decay either, for a different reason: the electron that the decay would make needs an empty state, and in the squeezed matter of a neutron star every electron state that the new electron could take is already full.

So we now have the second half of this chapter's answer. When a white dwarf or a neutron star is left to itself, it loses none of its matter to decay: it keeps its mass, goes cold, and stays held up, and nothing in it wears away.

## The Wasting Remnant, and This Account Beside It

The astrophysicists Fred Adams and Gregory Laughlin set out the best known picture of the future of the remnants. They published their picture in 1997, in a long review called "A dying universe". Their picture deserves to be told in its own terms, so I tell it first as Adams and Laughlin tell it. Adams and Laughlin accept that white dwarfs are held up by the exclusion of their electrons, and neutron stars by the exclusion of their neutrons. Adams and Laughlin hold that a white dwarf that has cooled is kept warm for a very long time by particles of *dark matter*, the unseen matter whose pull astronomers measure in every galaxy. Dark matter particles knock against the nuclei of the star, are captured, and destroy one another inside the star. Adams and Laughlin take as their working case that the proton decays, as the grand unified theories predict. A white dwarf powered by proton decay shines faintly by the energy the decay sets free, loses mass, and swells as it loses mass. Its matter turns toward lighter elements until, at about the mass of a giant planet, the white dwarf ceases to be a star at all. When a neutron star loses its mass in the same way, it comes in the end to resemble a white dwarf.

This physics agrees with the picture of Adams and Laughlin on what holds each remnant up, but this physics differs from their picture on three points, each for a reason of its own.

The first point is the dark matter. In this physics the dark matter never knocks against the nuclei of a white dwarf, so the dark matter gives the star no warmth.

The second point is the proton. In this physics the proton does not decay by any route, so the long wasting of the remnant that Adams and Laughlin describe has nothing to drive it, and the remnant keeps its mass.

The third point is how the forms of a remnant's matter, its protons, nuclei and electrons, come to an end. For Adams and Laughlin, the forms end by slow wasting. In this physics the forms end only at the end of the road the remnant travels: inside a black hole, or carried away alone.

## What the Dark Matter Is Here

Chapter 4 described the six small dimensions: six further directions at every point of space, curled up far smaller than an atom's core. In this physics the six small dimensions are part of the setting in which anything is found, and the shape at which the six are held fixes the forms that matter can take, such as the kinds of particle there are and the ways the particles join into atoms. In this physics the dark matter belongs to the six themselves. I identify the dark matter, in my book *The Weight of Possibility*, as a vibration of the six: a shiver of the setting, and not a particle of any of the forms that the setting fixes.

Think of a loom and the cloth woven on it. The frame of the loom fixes the pattern the threads can make. A shiver running through the frame is not a thread of the cloth. No thread can be caught on the shiver as one thread catches on another. In the picture, the frame of the loom stands for the six small dimensions, the threads stand for the particles of ordinary matter, and the shiver stands for the dark matter. The picture has one limit: a real frame that shook would shake its cloth, while the dark matter touches ordinary matter by weight alone.

The dark matter is like the shiver in the frame. A shiver of the setting is not one of the things in the setting, and nothing within an epoch turns a shiver of the setting into a thing in the setting. So dark matter never strikes a nucleus as one particle strikes another. The dark matter still carries energy, and everything that carries energy has weight. So the dark matter acts on ordinary matter through its gravity, and only through its gravity. In this physics, then, no white dwarf is kept warm by dark matter, because the dark matter never strikes the nuclei of the star.

## Two Roads for Every Remnant

A remnant does not sit still for ever in a quiet sky. Over the long ages a remnant's galaxy keeps stirring the remnant. Remnants pass close to one another and swing each other about. Some pairs of remnants spiral together and merge. Some remnants fall into a black hole. Other remnants are flung clear of their galaxy, and the expansion carries them beyond the reach of all other matter: they are carried away alone. So every remnant's path ends in one of two ways: inside a black hole, or carried away alone. I call the path of a remnant that remnant's road.

Our own galaxy has a giant black hole at its center, about four million times the mass of the Sun. Astronomers have pictured the giant black hole with the Event Horizon Telescope, a network of radio telescopes spread across the Earth. Adams and Laughlin worked from the way the stars of a galaxy slowly swing one another about, and they estimate that from one to ten in every hundred stars fall into the black hole at the center, and that the rest are thrown out of the galaxy. Adams and Laughlin and this physics agree on the two roads.

Some remnants travel part of their road by their own collapse. When a neutron star draws in more matter than its pressure can hold up, the neutron star collapses into a black hole. When a white dwarf is in a close pair of stars, it can draw matter from its partner up toward the Chandrasekhar mass. Then the carbon of the white dwarf ignites all at once, and the star blows apart as a supernova of the kind that Chapter 1 described, the kind that explodes with very nearly the same true brightness every time, which astronomers call Type Ia. The exploded white dwarf scatters its matter into the space around the star, and the same two roads lie before the scattered matter again.

## A Heavy Dwarf Alone

In 2020 the astrophysicist Matt Caplan followed one case further into the future by a calculation. Caplan published the calculation in the *Monthly Notices of the Royal Astronomical Society*. Caplan asked what becomes of a heavy black dwarf left alone, with no partner star to feed it matter, if protons never decay. In Caplan's calculation, nuclei inside the cold, crushed matter of the dwarf press against one another, and very rarely two of the pressed nuclei fuse by tunneling, the way a quantum particle crosses a barrier that it does not have the energy to climb. Caplan calls the fusion of nuclei pressed together by the density of the star *pycnonuclear fusion*. Caplan writes of the black dwarfs that over an immense time "pycnonuclear fusion will slowly process their composition to iron-56". Iron-56 is the nucleus of the commonest kind of iron.

The change to iron matters because of what holds the dwarf up. The electrons do the holding up, and the nuclei supply most of the weight. So the greatest mass a white dwarf can have depends on how many electrons it holds for each particle in its nuclei. Carbon and oxygen have one electron for every two particles of the nucleus, and iron has fewer: twenty-six electrons for fifty-six particles. As iron builds up in the dwarf, fewer electrons carry the same weight, so the greatest mass that the dwarf can have falls. Caplan finds that a dwarf left alone collapses in the far future if it is heavier than about 1.2 times the mass of the Sun. Caplan estimates the delay before the collapse at ten to the eleven hundred years, a one followed by eleven hundred zeros. If protons do not decay, Caplan counts the dwarfs that end by collapsing at about one percent of all stars in the observable universe.

Caplan's calculation and this physics agree on the point that is most important for the remnants: the matter of a remnant lasts. Fusion by tunneling destroys no proton or neutron. Fusion by tunneling builds heavier nuclei out of lighter ones, and along the way some protons take in elec-

trons and become neutrons, as protons do in the core of a collapsing star. The count of protons and neutrons together stays the same throughout. In Caplan's calculation, as in this account, no proton decays, so the collapse Caplan finds is a rearrangement of lasting matter, not a wasting away.

## The Last Glow of the Black Holes

What becomes of the black holes themselves? In 1975 Stephen Hawking published a calculation showing that a black hole gives off a faint glow, as a warm body does. By its glow, the black hole slowly loses its mass. The slow loss is called *evaporation*: the black hole shrinks by its own faint glow until, in the end, nothing of it is left. A heavier black hole has a colder glow and evaporates more slowly.

In 1976 Don Page worked out how fast a black hole loses its mass to Hawking's glow. For a hole with the mass of the Sun, Page's figure for the lifetime is about two times ten to the sixty-six years: a span of years written as a two followed by sixty-six zeros. By Page's calculation the lifetime of a black hole grows as the cube of its mass (the mass times the mass times the mass), so a hole ten times heavier lasts a thousand times longer. The longest-lasting black holes are therefore the giant ones at the centers of galaxies. Adams and Laughlin place the evaporation of black holes between ten to the sixty and ten to the hundred years. Adams and Laughlin place the coming apart of a galaxy, when its stars and remnants are flung out or swallowed, far sooner: between ten to the fifteen and ten to the twenty-five years. So the black holes are the last of the ashes to remain. Within the time the emptying of the sky takes, a black hole's glow gives back no remnant that the hole has taken in. The emptying comes first, by a margin of many powers of ten.

## The End of Each Road

We can now follow each remnant to the end of its road, inside a black hole or carried away alone.

Think first of an ice sculpture in a cold room. The cold around the sculpture holds the shape of the sculpture. Warm the room, and the shape is gone, while the water that the sculpture was made of does not vanish. In the picture, the sculpture's shape stands for the forms of matter. The cold of the room stands for the condition that holds the forms of matter, and the water for what goes on after the forms end. The picture has one limit, which matters: the water is still water. Past the end of each road, what goes on is no longer protons, nuclei or electrons.

The forms of matter are held in a way of the same kind as the shape of the sculpture. Protons, nuclei and electrons have the forms they have because the six small dimensions of Chapter 4 are held small. The six are held small while the large world of space and time is there around them, with things in that world to compare against. The condition that holds the six fails in two places: at the end of a black hole's interior, and for a body carried away alone.

When a remnant falls into a black hole, it crosses the black hole's horizon, the surface from inside which no signal can reach the outside, and inside that horizon the direction toward the center is the direction of time. So every path inside the horizon leads forward to an end. The end of the interior therefore comes after a finite time on the remnant's own clock, as a limit beyond which the smooth description of space and time no longer applies. The end of the interior lies at no moment of the outside world's time, so at the end of the interior the outside world has no moment at which the outside world could be there around the six, and nothing is there to compare against. So the hold on the six fails at the end of the interior.

A remnant carried away alone is carried by the expansion beyond the reach of all other matter. In the end everything else in the universe has passed beyond the edge of what the remnant can ever be compared with, so nothing is left within the reach of the remnant to compare against, and the condition that holds the six fails for the lone remnant too.

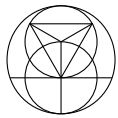
At either end, the six small dimensions are no longer held, and the forms of matter end with the hold on the six, but the matter does not vanish. I follow what becomes of the matter in Chapters 8 and 9. The end of the forms is no slow wearing away. The matter loses no proton and no electron to decay before the hold that gives the matter its forms comes to its own end.

## What This Means for You

The protons in your body are the same kind of particle as the protons in Sirius B and in the core of the Sun, and no proton in your body, in Sirius B or in the Sun will decay. Over spans of time far longer than the age of the universe, the atoms you are made of will be scattered, gathered into stars and remnants, and then drawn into a black hole or flung out alone. Through all of the scattering and gathering, no proton and no electron decays, and the count of protons and neutrons stays the same. The stars over the step will go out, but what the stars were made of will not wear away.

**Key idea.** White dwarfs and neutron stars are held up by exclusion, which needs no heat, so they cool and keep their size. The proton does not decay, because no carrier joins color to the weak charge. The electron lasts, and so do the neutrons inside nuclei and inside neutron stars. So each remnant loses none of its matter to decay until its road ends, inside a black hole or carried away alone, and the black holes evaporate last of all, far later. Matter keeps its forms until the hold that gives matter those forms ends, so matter does not wear away. The lasting of matter is important for the whole story of the far future. The lasting of matter means that the long emptying is a scattering and a gathering of matter, never a slow dissolving of matter.

And what happens to someone who is still there to watch?



Chapter 6

# What Happens to Someone Who Is Still There?

## The Last Watcher on the Step

Imagine the far future, and someone still standing on the back step, looking up. What happens to the watcher once the sky is empty? The galaxies have long since been carried out of sight, as Chapter 1 showed. The stars over the step have gone out, as Chapter 5 showed. The ashes of the stars have been gathered into black holes or flung away into the dark. The watcher is still there, under an empty sky.

The answer is short to state. The watcher's own road ends in one of the same two ways as the road of every remnant of a star, as Chapter 5 described those roads: inside a black hole, or carried away alone. To be carried away alone is to be carried by the expansion beyond the reach of all other matter. At either end, nothing is left within reach to compare against. So "standing still" and "turning" have nothing left to be measured against. "Before" and "after" between distant things have nothing left to be measured against either. One order stays. Each act of comparison runs one way, from the comparing to the record that the comparison leaves, and that one-way running is never reversed. Time does not stop:

no clock comes to a last tick. The end of the sky is the end of everything an observer can compare with, but the end of the sky is not the end of time.

## What an Observer Is

In Chapter 1 I gave the meaning that the word 'observer' has in this book. An observer is anything that compares one thing with another and registers what the observer finds, such as you on the step or an astronomer at a telescope. An observer need not be a person. An observer need not be alive either, because a camera or a photographic plate compares and registers too. The word "observer" needs a closer look now, because everything that follows depends on what an observer is, and on what this book means by the word "comparison", which the book has used from the start.

Every observation, every measurement and every test is a *comparison*: the act of finding whether two things are the same or different, in some respect. Someone who reads a thermometer this morning and again this evening makes one comparison. What an observer finds by a comparison is the comparison's *content*: in the case of the thermometer, the temperature, warmer in the evening than in the morning. The comparison's *context* is the respect in which the observer finds that content: the setting that makes the two things compared two. In the case of the thermometer, the two readings are two because they are taken at two times of day. So the two times of day are the context. Every reading needs a context. A reading taken at no time and at no place would be no reading at all.

An eye comparing one star with its neighbor is an observer at work. A gyroscope is a spinning wheel whose axis keeps one direction. A gyroscope holding its direction against the sky is an observer too. An observer at work can also be a person on a back step, noticing that the stars have wheeled a little since dusk. The eye, the gyroscope and the person on the step each compare, and each needs something to compare against. The

watcher on the step has always had plenty to compare against: the ground underfoot, the house behind, the stars and galaxies above, and the faint glow left over from the early universe. In the far future the watcher loses the ground, the house, the stars, the galaxies and the glow, one by one. We first need to see how much of what we take for granted is a comparison with the things around us, because only then can we see what happens to the watcher when the last of those things is gone.

## Mach and the Bucket

Chapter 4 described the six small dimensions: six further directions at every point of space, curled up far smaller than the core of an atom. Chapter 4 also said that the six small dimensions keep their shape, or are held, while the large world of space and time is there around them. The large world has things in it to compare against. What does that large world give an observer? First of all, an observer gets a standard of what it means to stand still and to turn. The large world fixes what counts as standing still and as turning, and I show why with the history of an old puzzle about a spinning bucket of water.

In 1883 Ernst Mach, a professor of physics in Prague, published a book on the history of *mechanics*, the science of motion. In that book Mach took up an old puzzle of Isaac Newton's. The puzzle was a bucket of water set spinning. Newton had described the bucket in his *Principia* of 1687, the book in which he set out his laws of motion. At first the bucket turns and the water does not, and the surface of the water stays flat. Then the water, too, comes to turn with the bucket. The water's surface curves into a hollow, climbing the walls. "This ascent of the water", Newton wrote, "shows its endeavour to recede from the axis of its motion". The hollow shows that the water registers its own turning, even at the stage when the water is not turning relative to the bucket. Newton took the hollow to show that the water turns relative to space itself, a fixed stage standing behind everything.

Mach read Newton's bucket experiment differently. He said that the turning of the water relative to the walls of the bucket produces no noticeable force flinging the water outward, and that the force comes from the turning of the water relative to the mass of the Earth and the other bodies of the heavens. So, on Mach's reading, Newton had shown only that the thin walls of a bucket are not what the water measures its turning against. Mach backed his reading with a question that no one could then answer: "No one is competent to say how the experiment would turn out if the sides of the vessel increased in thickness and mass till they were ultimately several leagues thick". For Mach, to turn is always to turn relative to something, and the something is the rest of the matter in the universe.

Two plain cases on the step show what Mach's question is about. Set a gyroscope spinning on a good mount, and its axis keeps pointing at the same distant stars while the Earth turns beneath the gyroscope. Turn round and round on the step until you are dizzy, and the organ of balance in your inner ear tells you, even with your eyes closed, that you are turning. In both cases something registers "turning" or "not turning". The gyroscope registers "not turning" by keeping its axis on the same distant stars, and your inner ear registers "turning". In this physics, as for Mach, the distant matter of the universe fixes what counts as "not turning". I give the reason in the next section. I call the standard that the distant matter fixes *rotation against the distant stars*: to be still or to turn is to be still or to turn relative to the matter far away, and the matter far away fixes what counts as not rotating.

## A Standard That Needs Something There

Einstein's theory of gravity is general relativity. The equations of general relativity do not by themselves determine the answer to Mach's question. The equations of general relativity have solutions that describe

worlds empty of matter, and in those worlds the equations still fix a standard of not rotating at each place, with nothing at all for that standard to be compared against.

In this physics the answer to Mach's question follows from a principle about comparison. Picture two rulers, one said to be a millimeter longer than the other, in a world where nothing could ever show the extra millimeter. If someone laid the two rulers side by side, the person would see no difference, no instrument would show the extra millimeter, and no effect of any kind would follow from the extra millimeter. A claim that the two rulers differ would then say nothing at all, because nothing anywhere could ever tell their two lengths apart. The principle is the case of the rulers made general: a difference that no comparison can register is no difference, because every distinction is made by comparison, and a distinction that no comparison can make is not a distinction.

Apply the principle to turning: where nothing is there to compare against, no observer can tell one standard of not rotating from another by any comparison, so a standard of not rotating is fixed only by matter within reach, meaning matter that an observer can still compare with. An observer's cosmological horizon is the edge beyond which nothing can ever send that observer a signal, as Chapter 1 described. Matter beyond that horizon can never be compared with the observer. So that matter fixes no standard for that observer.

The standard of not rotating comes from what lies within the horizon, so the watcher's sense of standing still rests on a comparison with the matter that the watcher can still reach. In what follows, to say that a distinction has nothing left to be measured against means exactly this: no matter remains within reach against which that distinction could be fixed. So the question about the last watcher can now be asked more sharply: what happens to the watcher when nothing is left within reach?

## Two Ways to Be Left

The watcher's surroundings change: the space around the watcher and the matter in that space do not stay as they are. Every observer belongs to some bound structure: a star, a galaxy, a group of galaxies. Each bound structure ends in one of two ways, body by body: each body in the structure ends inside a black hole, or is carried away alone, carried by the expansion beyond the reach of all other matter. Orbits shrink, close passes between bodies fling bodies outward, and the expansion of the universe carries off whatever is not bound. So every observer's road has two ends, and no third: the observer falls into a black hole, or the observer is carried away alone.

"Carried away alone" is a phrase that needs care, because of the picture that Chapter 1 gave of the horizon: each observer's cosmological horizon is like a skyline that the observer carries wherever the observer goes. An observer never crosses its own horizon, because the horizon is centered on the observer, moving with the observer. Instead, everything else crosses the observer's horizon: every other black hole, every remnant and the last of the radiation pass beyond the edge of what the observer can ever compare with. The lone observer is left with one reference only, its own horizon. The lone observer's horizon is fixed by where the observer itself is. No matter fixes that horizon.

The other end of every observer's road is a fall into a black hole. The region inside a black hole's horizon is the black hole's interior. Inside the interior, the direction toward the center is the direction of time, so every path inside leads forward to an end. So the end of the interior comes after a finite time on the falling observer's own clock: for a hole of the Sun's mass, at most about fifteen millionths of a second after the crossing. That end lies at no moment of the outside world. No signal from the end of the interior ever reaches the outside world, so nothing in the outside world can place that end before, at or after any moment of the outside world's

own time. The outside world has no moment at the end of an interior, so nothing in the outside world can be compared with anything there: the distant stars, the remaining black holes and the leftover radiation can no longer be compared with the falling observer at all.

So the observer is in the same condition at both ends of the road, inside a black hole and carried away alone. For the observer at the end of an interior, and for the observer carried away alone, no matter is left within reach against which a standard of rest, of what counts as standing still and as not turning, could be fixed. So "standing still" and "turning" have nothing left to be measured against at either end, and so "not rotating" then means nothing at either end, by the principle that a difference no comparison can register is no difference. Mach's bucket, set spinning at either end, would have nothing to measure its turning against.

## Will Time Ever Stop?

Jorge Cham is a cartoonist, and Daniel Whiteson is a physicist. Cham and Whiteson give one chapter of their book *Frequently Asked Questions About the Universe* (2021) to the question "Will Time Ever Stop?" Cham and Whiteson take the question seriously, and they lay out three things that an end of time might mean. First, an end of time might mean no more laws: "perhaps an end of time simply means the death of order. Cause and effect might no longer have any meaning". Second, an end of time might mean no more change: a universe frozen in whatever state the universe had reached. Third, an end of time might mean a plain end, time capped the way the direction north is capped at the North Pole, where there is no further north to go. Cham and Whiteson are open about the state of physics on the question. They close the chapter with a plain admission: "we don't really understand time".

In this physics one principle fixes the answers to both questions, Mach's question and the question of whether time will ever stop. The principle is the one stated earlier in this chapter: a difference that no com-

parison can register is no difference. Time has one direction, and in the world we know two things show that direction. One is the order inside every single act of comparison. The other is an order spread across the whole sky. At the end of the far future the order inside each comparison stays. The order across the sky has nothing left to be measured against.

## The Order Inside Each Comparison

Every comparison runs one way, in three steps. First there is a *stance*: the side from which the comparison is made, facing something to be compared. Second, the observer finds something from that stance. Third, what the observer finds is laid down as a record. The record shapes the stance from which the next comparison is made. Think of reading a letter: you open the letter, you read what the letter says, and what you have read stays with you when you pick up the next letter. In that picture, facing the opened letter is the stance. What you read is what is found, and what stays with you is the record. You cannot keep what a letter says before reading it. The one-way order of the three steps is an order of what comes first, not an order of clock time. The order of the three steps cannot be reversed. I identify the one-way order of the three steps with the one direction of time.

At the end of an interior, and for the observer carried away alone, the one-way order inside each comparison stays as it is, unreversed. At the end of an interior, the content that is there does not cease, as Chapter 8 shows. What is gone is anything for that content to be compared with. So no comparison is left to which the one-way order could apply. Yet the one-way order itself is not undone.

## The Order Across the Sky

The one direction of time also shows on the largest scale: the universe expands in that direction and not the other. The distant matter also serves every observer as a common reference, against which the observer places events far apart from each other as before or after one another, and as cause or effect. The observer's outside world is everything that can ever reach the observer. Across the whole outside world, the ordering of "before" and "after" rests on the distant matter as that common reference.

At the end of an interior there is no outside world to supply the common reference, while for the observer carried away alone, everything that could supply the common reference has passed beyond the horizon. So at both ends, "before" and "after" between distant things have nothing left to be measured against. The loss of "before" and "after" is plainest for the observer carried away alone. No observer anywhere can place anything that happens to the lone observer at the end of its road before, at or after any event elsewhere, because the lone observer lies beyond the horizon of every other observer.

This physics keeps one order of time and loses the use of another. The answer of this physics can be set beside the three possibilities that Cham and Whiteson lay out: no more laws, no more change, and a plain end. The order inside each comparison is kept, unreversed. What goes is narrower than an end of all order. What goes is the common reference that lets distant things be placed before or after one another. Cause and effect between distant events have nothing left to be measured against, while the one-way order of each comparison is untouched.

## No Last Tick

Does time stop, then, at the end of a black hole's interior? On the clock of the falling observer, the end of the interior comes after a finite time. The end comes as a limit. The smooth description of space and time holds all the way up to that limit, and the limit is the edge of that description. No clock records a last tick, after which it ticks no more. Think of marks on the way to a line: one mark at half the distance to the line, the next at half of what is left, then half again, and so on. All of the marks lie within a finite stretch, and no mark among them is the last one before the line. The falling clock's time is like that stretch, with the end of the interior in the place of the line. The clock's time is finite, with no last tick in it.

Chapter 4 gave that limit a name: the turn, the limit at which the interiors of all black holes end. The turn is a limit, not an event in time. Someone could register the turn as an event only by making a comparison across the turn, setting a moment before the turn beside a moment after the turn, the way someone sets a morning reading of a thermometer beside an evening reading. No comparison is ever made across the turn, for two reasons. The outside world of our epoch has no moment at the end of an interior, and the falling clock's own time ends at the limit that the clock approaches. How long the approach lasts, how fast things change along the way, and how hot the matter grows: all three apply to the approach toward the turn, and none of the three applies to the turn itself. So when someone asks "when" about the turn, the question has no answer. The turn does not happen at a time.

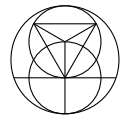
For someone still there in the far future, the sky empties until nothing is left within reach. Standing still and turning, and before and after between distant things, then have nothing left to be measured against, because each of them was always a comparison with the distant world. The order inside each comparison stays. No clock stops, and the turn that lies at the end is not a moment of any clock.

## What This Means for You

Your sense of standing still is a comparison with the rest of the universe. The steadiness of a gyroscope is a comparison with the rest of the universe too, and so is the dizziness that tells you, with your eyes shut, that you have been spinning. Your sense of which distant events came first rests on the same common reference, the matter far away. Each sense feels like a fact about you: your sense of standing still, and your sense of which events came first. Both senses are facts about you and the matter far away together. In the far future the matter far away passes out of reach, and then both senses have nothing left to be measured against. One order stays in the far future: the one-way order of every act of comparison, the order in which you find something and then know it.

> **Key idea.** An observer is anything that compares, and every observer's road ends inside a black hole or carried away alone. At either end nothing is left within reach to compare against. So "not rotating", and "before" and "after" between distant things, have nothing left to be measured against, while the one-way order inside each comparison stays unreversed. No clock comes to a last tick, and the turn is not an event in time. The end of the sky is the end of everything an observer can compare with, but the end of the sky is not the end of time. The rest of this book depends on the difference between the end of the sky and an end of time. When the sky of the far future goes dark, what ends is a world of things to compare with, and time does not end, so in the chapters that follow I ask what comes after that world.

Could a mind find a way to keep thinking even so, with nothing left within its reach to compare against?



Chapter 7

# Can a Mind Keep Thinking for Ever?

## The Watcher Who Wants to Keep Thinking

Can a mind keep thinking for ever, in a universe that goes on emptying? Go back to your back step once more, on a night very far in the future. The faint smudges of the other galaxies have gone, and the stars over the back step have gone out one by one. Suppose the watcher on the back step is a mind that wants to keep thinking about the sky for ever. The mind could think more and more slowly. The mind could spend less and less energy on each thought, and sleep for long stretches between thoughts. Would slowness and sleep let the mind think for ever?

In this physics the answer has two parts. The first part is about each thinker: no one thinker thinks for ever. Every thought is an actual comparison with something else. After the long emptying of the sky, every thinker has nothing outside itself to compare against, however large the thinker's store of energy. The second part is about thinking in the world at large. Comparison is the act of which every thought is made. Comparison does not stop when the thinkers of our epoch stop. Comparison begins again in the epoch that follows ours.

## Autumn 1978: Time Without End

In the autumn of 1978 the physicist Freeman Dyson, of the Institute for Advanced Study in Princeton, gave four lectures at New York University, the James Arthur Lectures on Time and its Mysteries. Dyson opened the lectures with a book: a year earlier the physicist Steven Weinberg had published *The First Three Minutes*, an account for general readers of how the universe began. Dyson quoted a line from Weinberg's book: "The more the universe seems comprehensible, the more it also seems pointless". Dyson answered Weinberg's line in one sentence: "If Weinberg is speaking for the twentieth century, I prefer the eighteenth".

Dyson said that, in the view that prevailed in his day, the future of every kind of universe was equally dismal: "we have only the choice of being fried in a closed universe or frozen in an open one". Dyson used "closed" and "open" for two fates of a universe. In Dyson's use, a closed universe is a universe whose expansion stops and turns into a collapse. An open universe is a universe that expands for ever. (In Chapter 2 the words "closed" and "open" named two shapes of space. In the universes that physicists studied in Dyson's day, which had no energy of empty space, the closed shape went with the collapse and the open shape went with expansion for ever.) Dyson agreed that a closed universe offers no escape from the frying, the heat of the final collapse. Of an open universe Dyson wrote that "my philosophical bias strongly favors an open universe", and he asked three questions about an open universe. First, does an open universe freeze into a permanent quiet as the universe expands and cools? Second, can life and intelligence survive in an open universe for ever? Third, can societies keep sending messages to one another across the ever greater distances of an open universe? Dyson answered the three questions in one sentence: "Tentatively, I shall answer them with a no, a

yes, and a maybe". So Dyson's answer was no to the first question, yes to the second and maybe to the third. The journal Reviews of Modern Physics printed the lectures in 1979, under the title "Time without end".

## Slower, Colder, and Asleep

Dyson answered yes to the second question, whether life and intelligence can survive for ever, and his yes depends on one assumption about life. Dyson assumed that what makes a creature conscious is the way the creature is put together, and not the particular stuff the creature is made of. From that assumption Dyson drew what he called his *biological scaling hypothesis*, a claim about what happens to a copy of a living creature. Copy a living creature, every part of it, so that the copy runs on a smaller scale of energy, and then put the copy in surroundings colder by the same factor by which the copy's scale of energy is smaller. In Dyson's words, "the copy is alive, subjectively identical to the original creature, with all its vital functions reduced in speed by the same factor". In plain words, a thinker built to run colder thinks the same thoughts as the original thinker, more slowly, and spends less energy on each thought. Dyson counted a creature's life in what he called *subjective time*: time as the creature itself lives it, which in Dyson's scheme runs more slowly, against the clocks of the universe around the creature, as the creature runs colder.

Running colder has a limit, and Dyson found the limit. A thinker must get rid of the waste heat of its thinking by radiating the heat away. The colder a body is, the more slowly it can radiate. Dyson measured how much a creature thinks by the number of yes-or-no choices the creature must make in each moment of its own time. For a thinker that makes a fixed number of yes-or-no choices in each moment of its own time, there is a lowest temperature at which the thinker can still shed the heat of its thinking all the time. Below that lowest temperature the thinker makes heat faster than the thinker can radiate the heat away, so a thinker that thinks all the time cannot keep running colder as the universe cools.

Metabolism is the chemical work by which a living thing uses its energy. Under Dyson's scaling hypothesis, a creature's metabolism slows as the creature runs colder. "We have reached the sad conclusion", Dyson wrote, that "the slowing down of metabolism described by my biological scaling hypothesis is insufficient to allow a society to survive indefinitely".

Then Dyson wrote: "Fortunately, life has another strategy with which to escape from this impasse, namely hibernation". In Dyson's sense, *hibernation* is thinking in bursts. A society that hibernates thinks for a short stretch and then sleeps, and while the society sleeps it uses almost no energy and keeps radiating away the heat of its last burst of thinking. As the universe cools, the society runs colder, and the society makes its waking stretches a smaller and smaller share of the time. Dyson showed that the society can choose its schedule of waking and sleeping so that two things are true together. In Dyson's words, the first of the two things is that "subjective time goes on forever". The second of the two things is that "the total energy required for indefinite survival is finite". For a society as complex as ours, Dyson calculated that the whole store of energy that the society needs for ever is "about as much energy as the sun radiates in eight hours".

Dyson asked one thing more of an endless life: a memory that never fills. A memory can be written in separate marks, like letters on a page, but a memory of that kind is limited by the number of atoms from which the memory can be built. So Dyson turned to a memory written in a smooth quantity, such as an angle, whose value can be read to more and more figures as the universe grows colder and quieter. Dyson called a memory of that kind an *analog memory*, and he wrote that "there is no limit in principle to the capacity of an analog memory built out of a fixed number of components in an expanding universe". On the third question, whether societies can keep sending messages across ever greater distances, Dyson found that a society could keep signaling to a distant society on a finite store of energy. Dyson also found that chains of societies

could pass messages along over any distance. In Dyson's words, "It is in principle possible to communicate forever with a remote society in an expanding universe, using a finite expenditure of energy".

Dyson worked out these results on slowing, sleep, memory and messages for the universe that he took to be ours. Dyson's universe expands for ever and has no cosmological constant, the steady energy of empty space that Chapter 1 described, and in Dyson's universe each observer's horizon keeps growing, so that more and more galaxies come into view as time goes on.

## The Reply: A Horizon and a Floor

Twenty years after Dyson's lectures, the universe as astronomers measured it had changed. The expansion of the universe is speeding up, driven by a cosmological constant, as Chapter 1 described. Lawrence Krauss and Glenn Starkman were physicists at Case Western Reserve University in Cleveland. In February 1999 Krauss and Starkman sent out a paper that applied Dyson's plan to a universe whose expansion speeds up. Krauss and Starkman called the paper "Life, the Universe, and Nothing", and The Astrophysical Journal published the paper in 2000. The first sentence of the paper reads: "Current evidence suggests that the cosmological constant is not zero, or that we live in an open universe". Krauss and Starkman took Dyson's biological scaling hypothesis as their main tool. Krauss and Starkman asked what a thinker can do in a universe where every observer has a horizon. Krauss and Starkman's reply has four parts: the horizon, a floor of temperature, sleep, and limits on memory and on steps.

The first part of the reply is the horizon. Physicists call a universe whose expansion is driven by a cosmological constant a *de Sitter universe*. In a de Sitter universe each observer has a horizon beyond which no signal will ever arrive, and Krauss and Starkman wrote: "Objects more distant than the de Sitter horizon now will forever remain unobservable". A

civilization can therefore gather only a fixed amount of matter and energy, because nothing beyond its horizon can ever reach the civilization. The amount is very large by human standards, but finite.

Krauss and Starkman's reply has a second part: a floor of temperature. In a de Sitter universe the horizon itself glows, very faintly, so empty space keeps a temperature that never falls away. The physicists Gary Gibbons and Stephen Hawking found the glow of the horizon in 1977. Picture a room whose walls stay faintly warm for ever. A thing in the room can cool below the temperature of the walls only by running a refrigerator. The refrigerator costs more energy than it saves. The walls of the room are the glowing horizon, and the things in the room are the thinkers inside the horizon. Krauss and Starkman wrote that "the de Sitter temperature fixes a minimum temperature below which life cannot operate" without a refrigerator. Under Dyson's plan, a thinker uses less energy only by running colder. So a thinker held at the floor of temperature cannot keep lowering its use of energy. A finite store of energy then pays for only a finite amount of thinking.

Krauss and Starkman's reply has a third part: sleep. A sleeper sheds its heat during sleep only by staying in touch with something colder than itself. The coldest thing in the sky is the afterglow of the Big Bang, the faint warmth from every direction that Chapter 1 described. Physicists call the afterglow the background radiation. Over all future time a body receives only a finite amount of the background radiation, so the sleeper loses touch with the background radiation. A sleep also needs something to end it, such as an alarm clock. "Alarm clocks are eventually guaranteed to fail", Krauss and Starkman wrote. Krauss and Starkman went on: "In the absence of a sentient being to repair the broken alarm clock, hibernation would continue forever".

Krauss and Starkman's reply has a fourth part, and the fourth part has the widest scope. The fourth part applies first to the memory of every thinker, and then to every finite system. A memory of finite size fills up, and a thinker that keeps taking in its world must clear old contents to make room. Picture the memory as a long row of switches, where each

switch is one mark of the memory. Before using the row again, the thinker sets every switch to off. Setting every switch to off is clearing the memory. Many arrangements of the switches have become one arrangement, and the many have to go somewhere: into the surroundings, as heat. Physicists measure the cost of clearing a memory with a quantity called *entropy*. Entropy is a count of the arrangements of a thing's parts that leave the thing looking the same from outside. Every clearing of a memory raises the entropy of the thinker's surroundings, and the thinker must shed the heat that carries the entropy away, but a thinker out of touch with anything colder than itself cannot shed heat for ever.

Krauss and Starkman also found a limit that is simpler and more basic than the limit of heat. In this book a *computation* is one rule applied the same way, step after step. To take endlessly many distinct steps on a finite store of energy, a thing would need endlessly many distinct conditions to pass through, packed ever closer together in energy, and Krauss and Starkman wrote that "no finite system has such a property. Hence, no finite system can perform an infinite number of computations".

In the abstract of "Life, the Universe, and Nothing", Krauss and Starkman conclude that "the integrated conscious lifetime of any civilization will be finite". Krauss and Starkman judge Dyson's hope in one short sentence: "The eternal expansion which Dyson found so appealing is a chimera", and a chimera is a creature of fancy. Krauss and Starkman left aside the possible strong effects of gravity through black holes, and they did not try to follow those effects.

## What a Thought Needs

Now set Dyson's question, whether a mind can keep thinking for ever, inside the physics of this book. In this book, as Chapter 1 set out, an observer is anything that compares one thing with another and registers what it finds, an atom or an instrument as much as a person. I also call

anything that compares a *comparer*. An observer, or comparer, need not be a mind. A mind is a comparer of a particular kind, and this physics says what kind of comparer a mind is.

Picture yourself on your back step, hearing a piece of music for the first time. Each note arrives after the note before it, and the first hearing of the piece cannot be had again. Some notes surprise you, because nothing you heard before fixed them. And the hearing is yours: the music happens to someone. The hearing has three features: the notes arrive in one order, some notes are fixed by nothing before them, and the hearing happens to you. The three features belong to every act of comparison, and the three features come together. Every act of comparison runs one way, from the comparing to the record that the comparing leaves. The outcome of every act of comparison is something that nothing before the act fixed. And every act of comparison is made from a stance: the side from which the comparison is made, the side to whom the outcome happens. Take any one of the three features away, and the other two go with the one taken away. When you hear the music, the three features come to you as one hearing and not as three separate things one after another. In the one hearing the note arrives, nothing fixed the note in advance and the note arrives to you, all in one act. A context is the respect in which a comparer finds what the comparer finds, as Chapter 6 set out. When the three features are taken whole, as in the hearing, in a context and as one act happening, the three features are what I identify as *consciousness*. So consciousness, in this book, is the three features held together as one act, as the hearing holds the note (the one-way order), the surprise (the outcome that nothing fixed) and the listener (the stance) together.

When a thing has the three features together, this book says that the thing has an *inside*: a side of its own, from which the comparing is done and to which the outcome happens, as the music happens to you. My book *What Cannot Be* is the book of this collection on the limits of computation, and in that book I show that only a physical process making comparisons in the world can have an inside, as living things do. In *What Cannot Be* I also show that whether a thing has an inside "never depends on

which program it runs". So a thinker of the far future thinks only as a physical process making comparisons, whatever its material and whatever its temperature. A count of computations is therefore not a count of thoughts, because a thought is made by a physical process making comparisons, and not by the program that the process runs.

What does one act of comparison need? I build the smallest comparison there can be, in a universe otherwise empty, in *Why the Quantum Is the Way It Is*, another of my books in this collection. Two hydrogen atoms sit some distance apart, and the first atom gives out a single particle of light, a *photon*. The second atom takes the photon in, and the electron of the second atom is lifted to a higher level. Then I take the picture apart, one piece at a time, to find what the comparison needs. Remove the first atom, and the second atom has nothing to be measured against. Remove the proton from the second atom, and there is no bound atom left to keep a record of what arrived. Remove the photon, and nothing passes between the atoms at all. So even the smallest comparison needs three things: a second thing to compare against (the first atom), a lasting structure in which the record is kept (the bound second atom), and a signal between the two (the photon). I put the point in one line in *Why the Quantum Is the Way It Is*: "a comparison needs an actual interaction, not a possible one".

Energy also has a place in this physics. The place of energy determines whether a large enough store of energy can let a thinker think for ever. I state the place of energy in one sentence in *Comparison; The Necessary Basis*, another book of this collection: "Energy is the capacity of a system to participate in comparisons". A store of energy, however large, is a capacity. A capacity to take part in comparisons is used only where there is something there to compare with. So the size of the store will not decide whether a thinker's thinking goes on.

Time has a place in this physics too. Imagine a completely empty universe that holds two things, a head with an eye in it and a book. Let nothing change. Take two moments in that universe. Nothing differs between the two moments, so they cannot be told apart. To tell the two moments apart, something has to change. A change can be found only in the flow

between the head and something else, in the perceiving itself. The perceiving is a comparison. In *What Cannot Be* I put the point in these words: "Time comes with the comparison, not before it". In *What Cannot Be* I also write that, for someone perceiving, "the felt passage of time goes with the number of changes, and with how much is new, in what is perceived". When one act of comparison yields one outcome, laid down as a record, this book calls the outcome a *finding*. So in this physics Dyson's subjective time has a counterpart: a count of findings, each finding made against something there to be found.

Put the three parts together (what one comparison needs, the place of energy and the place of time), and "thinking for ever" has a plain meaning in this physics. The phrase means an endless run of findings by one thinker, each finding made against something actually there, and each finding kept in a lasting structure of the thinker's own.

## What the Emptying Leaves a Thinker

Now follow the thinker through the long emptying of the sky. Every thinker belongs to a bound structure such as a planet, a star or a galaxy, held together by its own gravity. Every observer's road through the far future has two ends, and no third, as Chapter 1 showed and Chapter 6 followed in detail. The thinker falls into a black hole and comes to the end of the black hole's interior, or the thinker is left alone while everything else passes beyond the thinker's horizon. I put the point in one line in my book *The View from Inside*, another book of this collection: "So every path through the space between has two exits, and no third".

Could the fall into a black hole at least last for ever on the thinker's own clock? The fall cannot last for ever, even on the thinker's own clock. Inside a black hole's horizon, the way inward is the way forward in time, so on the clock of a body that falls in, the end of the interior comes after a finite time, as a limit. For a black hole of the Sun's mass, the standard calculation in Einstein's theory of gravity puts the end of the interior at most

about fifteen millionths of a second after the crossing of the horizon. The end of the interior lies at no moment of the outside world's time, so at the end of the interior nothing of the outside world is there to be compared with. A thinker carried away alone keeps one reference only: its own horizon, fixed by the thinker's own place and by no matter. The thinker carries its horizon with it, as you carry your own skyline wherever you walk. So at either end, inside a black hole or alone, the thinker has nothing outside itself to compare against.

At either end the thinker also loses something more than a world to compare against: the forms of its own matter. Matter in our epoch takes forms such as atoms, molecules and cells. The six small dimensions are six further directions at every point of space, curled up far smaller than the core of an atom (Chapter 4). In our epoch the six are held at one size and one shape. The forms of matter depend on the six small dimensions keeping their held shape. While the large world of space and time, with things to compare against, is there around the six, the six are held. The condition that holds the six fails in two places. One place is the end of a black hole's interior. The other place is a body carried away alone, when nothing is left within the body's reach to compare against. In both places the six small dimensions are no longer held, and the forms of matter end when the hold on the six ends. A lone particle in the far future stops being matter in the form that our epoch gives matter. What the particle was made of does not stop being. A thinker is made of matter in our epoch's form, and the thinker keeps its records in structures made of that matter. So at either end the thinker loses two things: anything outside itself to compare against, and the structure in which the thinker compares and keeps its records.

Put the steps of this section together (the two ends, the finite fall and the loss of the forms of matter), and the answer about each thinker is plain: no thinker makes an endless run of findings. Each thinker comes to a condition with nothing outside to compare against. In that condition the forms of the thinker's own matter are not held. A thinker comes to that

condition even with an endless store of energy, running as cold and as slowly as it likes. The conclusion uses none of three things: the thinker's store of energy, its temperature and its speed of thinking.

## Dyson's Three Questions

This physics has an answer to each of Dyson's three questions, and I take the questions in the order second, third, first, because the first question belongs to the next chapter.

Dyson's second question was whether life and intelligence can survive for ever. No one thinker can survive for ever, for the reasons set out in the section before this one: at either end of its road a thinker has nothing outside itself to compare against, and the forms of its own matter are no longer held. Krauss and Starkman reached the answer no from a finite store of energy and a floor of temperature, but in this physics the answer no follows without either: the size of the store and the temperature do not enter this physics' argument.

Dyson's third question was whether societies can keep sending messages across ever greater distances. The speed of light sets the outer edge of what any comparer can compare with, because every act of comparison needs a signal between the two things compared and no signal travels faster than light. In a universe whose expansion speeds up, the horizon cuts every observer off from what lies beyond the horizon: no signal from beyond an observer's horizon will ever reach the observer. Picture a message sent toward a society beyond the horizon: the message is like a runner on a track that grows longer ahead of him faster than he can run, and he runs for ever and never arrives. The runner is the message, and the track ahead of the runner is the distance to the far society, which the expansion stretches faster than the message can cover the distance. So no chain of societies passes a message to a society beyond the horizon of the society that sends the message.

Dyson's first question was whether the universe freezes into a permanent quiet. Dyson's first question is the question of the next chapter, Chapter 8: is the long emptying the end? I answer the question in Chapter 8.

One more question belongs in this section, because Krauss and Starkman left the question aside: could a thinker escape through a black hole? A black hole cannot carry a thinker out of our epoch as a thinker. A thinker that falls into a black hole comes to the end of the black hole's interior, where the forms of the thinker's matter are no longer held and nothing is left to compare against. The turn is the limit at which the interiors of all black holes end, as Chapter 4 set out. No act of comparison spans the turn either.

## Where Thinking Begins Again

In this physics the long emptying is followed by a new epoch with the same structure as ours. I give the reasons in Chapter 8. I need only what the new epoch means for thinking.

The structure that I derive is the same in every epoch. In every epoch the six small dimensions have the same shape, and the same size counted in Planck lengths. The Planck length is the unit of length that the strength of gravity sets. I follow the new epoch onward in my book *At the Edge of Reality*, another book of this collection: "Then the new epoch makes stars, and the stars make black holes". In the new epoch acts of comparison happen. Every act of comparison in the new epoch has the three features that our acts of comparison have: a one-way order, an outcome that nothing before the act fixed, and a stance. So in the sense of this physics, comparers are present in the next epoch as comparers are present in ours. The new epoch also begins with the same structure and the same orderly start under which stars, planets and people became possible in ours.

Whatever thinking happens in the next epoch belongs to the next epoch alone. In this physics, to be *real* is to be given in an actual act of comparison, here and now. No act of comparison in the next epoch takes in any finding of our epoch, because no act of comparison spans the turn. So nothing of any thinker of our epoch is real in the next epoch: no finding, no record and no count. The thinking of the next epoch continues no thinker of our epoch.

A next epoch follows ours, and another epoch follows the next one. Thinking goes on for ever in this sense: each epoch is followed by a next epoch, and in each epoch comparison begins again. The cycle of epochs has no first turn. I speak of the epochs one after another, never of all the epochs gathered into one finished whole.

## What This Means for You

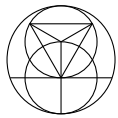
Every thought you have is made against something there: a page, a face, the sky over your back step. Your thinking is a physical process with an inside, joined to a world that your thinking can compare with. Your thinking belongs to this epoch as the sky does. No plan of slowness or of sleep stretches one thinker's run of findings without end, Dyson's plan included. No plan needs to, because comparison itself is not used up: comparison begins again in every epoch that follows ours.

**Key idea.** A thought is an actual comparison with something else, kept in a lasting structure of the thinker's own. After the long emptying of the sky, every thinker is either at the end of a black hole's interior or alone. At either end there is nothing outside to compare against, and the forms of the thinker's own matter are no longer held, whatever the thinker's store of energy, its temperature or its speed. So no one thinker thinks for ever, and no thought crosses into the next epoch. Thinking goes on, because in each epoch that follows ours, comparison begins again. This chapter's answer matters because the answer shows where the thinking of the far future ends, in the long emptying, and why the end of every thinker is not the end of thinking.

Why can the long emptying not be the end of everything, a dark that stays dark for ever?

# PART TWO

*After the Dark*



Chapter 8

# Is the Long Emptying the End?

## The Dark Sky Is Not Where the Story Stops

Why can the long emptying not be the end of everything, a dark that stays dark for ever? Stand on the back step once more, on the last clear night there will be. The smudges of the other galaxies have gone beyond the horizon, the edge beyond which nothing can ever send you a signal, and the stars over the step have gone out. Chapter 6 found that a watcher on the step on that last night has nothing left in the sky to compare against. Popular books on the end of the universe stop the story on that last night. In those books the sky stays cold and dark for ever. The cold, dark sky is a true view of the future as far as the view goes, because the dark sky is how the future looks from inside our epoch, the era of the world whose history runs back to the Big Bang. But the dark sky is not where the story of the universe stops.

Part One of this book followed the long emptying of the sky. The long emptying ends at what this book calls the turn. Chapter 4 named the turn: the limit at which the interiors of all black holes end, a limit approached from both sides, the side of our epoch and the side of the next epoch, and reached from neither side. The turn is not an event that any history passes through. The next epoch begins from the turn. Three grounds show that the dark cannot be final. Each ground is enough by itself, without the oth-

er two. The first ground is that content, what a comparison finds, cannot be without a context, the respect in which the comparison finds the content. The second ground is that a featureless emptiness, the same everywhere and with no break anywhere, is the one thing that no observer ever finds by any comparison. The third ground is that every entropy is a count made against a context. So when the context has emptied, the count has nothing left to be counted against.

## Edinburgh, 1852: The Old Fear

The fear that the universe runs down is older than the knowledge that the universe expands. On 19 April 1852 a short paper by the physicist William Thomson was communicated to the meeting of the Royal Society of Edinburgh, that is, presented to the members of the society. Forty years later Thomson was made Lord Kelvin. Thomson is best known by the name Kelvin. Thomson called his paper "On a universal tendency in nature to the dissipation of mechanical energy". Mechanical energy is energy that can do work, that is, push or lift something: the energy of a turning wheel or of a raised weight. To *dissipate* mechanical energy is to spread the energy out as heat, in a form from which no more work can be drawn. When a brake stops a wheel, the warmth left in the brake is dissipated energy. The warmth is the energy of the turning wheel, spread out as heat.

Thomson stated his first conclusion in one line: "There is at present in the material world a universal tendency to the dissipation of mechanical energy". In his third conclusion Thomson looked ahead: within a finite time to come, he wrote, the earth must again be "unfit for the habitation of man as at present constituted", unless something happens that the known laws of the material world do not allow.

Thirteen years later, in 1865, the German physicist Rudolf Clausius gave the spreading of energy a measure and a name. Clausius called the measure entropy, from the Greek word for a transformation. Clausius closed a long paper in the journal Annalen der Physik und Chemie with

two sentences, written in German, which read in English: “The energy of the universe is constant. The entropy of the universe tends toward a maximum”.

When Clausius’s two sentences were put together, the far future of the whole universe looked plain: every difference of temperature evens out, every store of usable energy spreads into one lukewarm sameness, and nothing is left that could drive any change at all. The Preface called that end the heat death of the universe: a final state in which everything has one temperature, the entropy of everything has reached its largest value, and nothing ever happens again. Chapter 7 defined entropy as a count of the arrangements of a thing’s parts that leave the thing looking the same from outside. Chapters 1 to 6 followed the long emptying of the sky. The long emptying is the modern form of the same picture of the heat death. In the long emptying the sky goes dark, the count of entropy rises, and the watcher on the step is left alone.

## What Is Left When the Sky Is Empty

Where exactly does the long emptying leave each observer? In this book an observer is anything that compares one thing with another and registers what it finds (Chapter 1). Chapter 1 found, and Chapter 6 followed in full, that every observer comes to one of two ends. The observer falls into a black hole and approaches the end of the black hole’s interior, or the observer is carried away alone while everything else passes beyond the observer’s horizon. The lone observer is then in the same position as an observer on its final approach to the end of a black hole’s interior. For each of the two observers, the large world has ceased to be anything to compare against.

The world as a whole has ten dimensions: the four large dimensions of space and time, and the six small dimensions that Chapter 4 described. The six small dimensions are six further directions that every point of space carries, curled up far smaller than the core of an atom. The held

shape of the six small dimensions fixes the forms that matter can take, such as atoms, stars and bodies. The six small dimensions are held, kept at one fixed size and shape, while the large world of space and time is there around them, with things in the large world to compare against. In two places, the six small dimensions no longer have a large world around them with things in it to compare against. One place is the end of a black hole's interior. The other place is a body carried away alone, which the expansion has carried beyond the reach of all other matter, so that nothing is left within the body's reach to compare against. In both places the six small dimensions are no longer held.

Physicists describe the world in two ways. The smooth description of gravity is Einstein's theory, which treats space and time as smooth. The quantum description is the physics of the very small. At the end of a black hole's interior, the bending of space and time reaches the Planck scale, the scale of length, time and energy at which gravity and the quantum meet on equal terms. At the Planck scale both descriptions reach the edge of the range in which each description holds. Neither description takes over from the other. The edge is an edge of the two descriptions, and not an ending of the world that the two descriptions describe.

Chapter 6 called what a comparison finds its content, and the respect in which the comparison finds its content its context. In physics, the content is the matter and light of the world, because matter and light are what observers find by their comparisons, and the context of the matter and light is the arena of space and time, with the outside world in that arena. Chapter 6 found that at the end of the emptying nothing is left that a comparer, anything that compares, could compare with. Yet at the end of each black hole's interior, the matter and light that fell in have not ceased to be. The content is still there, and no large world is left to be its context. The three grounds of this chapter apply to exactly that case: content still there, with no large world left around it as its context.

## The First Ground: No Content Without a Context

Go back to the thermometer of Chapter 6, read this morning and again this evening. The thermometer compares this morning's warmth with this evening's warmth. The temperature that the comparison finds is the content, and the two times of day are the context. A temperature is always found at some time and at some place. A temperature found at no time and at no place is no finding at all.

This physics states the structure of every comparison in three axioms, and the axiom this chapter needs is the third. The *third axiom* holds content and context distinct and inseparable. There is no content without a context in which it is content, and no context without a content. In plain words, content and context are two different things, and neither is ever found without the other. Content and context are found by looking at what any comparison contains, and so is the bond between them that the third axiom states. The thermometer shows content and context together: the reading of the thermometer contains a content, the temperature, and a context, the two times of day.

Now put two facts side by side: the content does not cease at the end of the emptying, and the third axiom excludes content without a context, so a context must form again. What can the new context form from? At the end of the emptying the old outside world offers nothing to form a context from, and the forms of matter have ended, because the six small dimensions are no longer held. Two things remain: the content, and the ten-dimensional geometry itself. The content cannot be its own context, because the third axiom holds content and context distinct, so the new context forms from the ten-dimensional geometry. I put the restoring of a context in two short sentences in my book *At the Edge of Reality*: "When the conditions fail, the ten-dimensional geometry restores a large outside context. It must".

How does the ten-dimensional geometry restore a large outside context? Picture a seesaw, with the three directions of space on one end and the six small dimensions on the other end. Inside a black hole, as the end of the interior comes near, the seesaw tips one way. The seesaw is a picture of an exact solution of Einstein's equations, written for all ten dimensions, on which the three directions of space shrink while the six small dimensions grow. The new world then begins with the seesaw tipping back: as the new world's own time runs forward, away from the turn, the three directions of space of the new world grow while the six shrink back to their held small size. The same rule of change describes both histories, with the same powers. Each size grows or shrinks in proportion to a power of the time, and the powers are the same in both histories. But one history runs toward the limit at the turn, and the other history runs away from that limit.

The three large directions of the new world are new. No direction of the new world continues any direction of the old world, large or small. The ten dimensions split again into four large and six small, out of a geometry in which the new world had no separate identity. The restoring of a large world is a step in a cycle, because the same conditions that ended the old outside world require, by the third axiom, a new outside world to form.

## The Second Ground: A Featureless Emptiness Is Never Found

The second ground is that a featureless emptiness is never found. The second ground comes from a different source than the first ground, which came from the third axiom. The second ground begins with four everyday words, each with a picture. A ramp is *continuous*: it rises without a break, with no sudden step anywhere. A staircase is *discontinuous*: it rises in separate steps. A law that holds in every city is *symmetric*: it stays the same

through the change from one city to another. A diary is *asymmetric*: every page differs from the last, and nothing in a diary stays the same from page to page.

The *Incommensuration Theorem* says that, at the foundation of any comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing. The theorem holds wherever a comparison is made. Every measurement is a comparison, so the theorem holds for every measurement. The words "at the foundation" mean: in what a comparison finds when the comparison is taken all the way down, exactly and not approximately. Things in the world show symmetry and continuity together, approximately, all the time. Yet no observer ever finds, by any comparison, both symmetry and continuity perfect at once. The theorem's first half applies to the emptying: the half about symmetry and continuity.

A flat map of the whole Earth has a limit of the same kind as the theorem's limit: two perfections that cannot both be had at once. Keeping every angle true is one perfection of a flat map, and keeping every area true is another. A flat map can have either perfection, but no flat map has both. In the picture, the flat map stands for a comparison. The two perfections of the map stand for symmetry and continuity, the two perfections of a comparison. No observer finds both perfections at once in any comparison: every comparison falls short of perfect symmetry or of perfect continuity somewhere, as every flat map falls short of true angles or of true areas somewhere.

Now picture the heat death taken to its end, as popular books on the end of the universe picture it. A final world of featureless emptiness would be the same everywhere and at every moment, with nothing in it different from anything else. The final world would also be smooth everywhere, with no break or step anywhere. So a world of featureless emptiness would be perfectly symmetric, because it is the same everywhere, and perfectly continuous, because it has no break, both at once. In my book *The View from Inside* I name that combination of perfect symmetry

and perfect continuity: "the one character no comparison ever finds". So, by the Incommensuration Theorem, the emptying cannot come to rest in a world of featureless emptiness. I write in *The View from Inside*: "The emptying cannot simply come to rest. Context must be restored".

The Incommensuration Theorem also limits how the new large world can begin. The new large world cannot begin perfectly even either, because perfect sameness in every direction and at every place would make symmetry and continuity both perfect. So the new large world begins even except for very small unevennesses. Chapter 9 describes the very small unevennesses.

## The Third Ground: Every Count Has a Context

The third ground is that every count of entropy is made against a context. The third ground is about entropy itself, the quantity at the center of the old fear: Clausius said that the entropy of the universe tends toward a maximum. What exactly does an entropy count? A state of a thing is one complete arrangement of the thing's parts. An entropy is a count of the states of a thing that an observer cannot tell apart by the comparisons available from some context: the arrangements that leave the thing looking the same from that context. So an entropy is always a count made against a context. A change of context is a change of what is counted, and a count made against one context is not a count made against another context.

Within our epoch the count of entropy grows, as Clausius said the count would grow. Stars burn, galaxies gather, black holes grow, and the counts rise toward their largest values at the end of the epoch. The rise of the counts is the direction of heat that anyone can see in a kitchen: a hot cup cools, the ice in a glass melts, and neither change goes back.

The largest counts of all belong to black holes. The physicists Jacob Bekenstein and Stephen Hawking worked out the standard formula for the entropy of a black hole, in 1973 and 1975. The formula gives every

black hole an entropy, and for a large black hole that entropy is enormous. I identify what the entropy of a black hole counts as the states of the black hole's interior that no comparison from outside can tell apart. So the entropy of a black hole is a count made against the outside world as its context. Physicists call a standard theorem of gravity the *no-hair theorem*, and the no-hair theorem shows why the count is so large. Once a black hole has settled, all that an observer outside can register of the black hole is its mass, its electric charge and its spin, how fast it turns. Every arrangement of the black hole's inside that has those three values looks the same from outside. The entropy of the black hole counts the arrangements that share one mass, one electric charge and one spin. The end of a black hole's interior lies at no moment of the outside world's time, so at the end of the interior nothing of the outside world is there to count against. I write in my book *The Gravitational Passage* that "the count has no reference left". Matter outside the black holes has an entropy of the same kind: a count made against the same outside world, and that outside world ends.

Think of a census, in which clerks count what they can tell apart, by the categories that their own forms record. When a new country is founded, with new clerks and new forms, the first census of the new country does not continue the census of the old country: the first census of the new country starts its own count. In the picture, each country stands for an epoch, the clerks and their forms stand for the comparisons available from the epoch's context, and each census stands for an entropy, a count made against that context. An epoch's entropy tends toward a largest value, and that largest value is counted against the epoch's own outside world. When the epoch's outside world has emptied, the largest value has nothing left to be the largest value of, and the next epoch begins its own count against its own context.

The content itself is carried across the turn, from the collapse on one side of the turn to the new world on the other side, but no count made against the old outside world passes the turn. I state the reset in one line in my book *The Gravitational Passage*: "The new context does not register the distinctions the old context drew, and that is the reset". Nothing is

destroyed at the reset, because the content passes the turn. The only thing that does not pass is a count made against a context that has ended. Clausius's sentence about entropy holds inside every epoch, as a statement about counts made against that epoch's context. But the heat death would be a final maximum that holds for ever, and such a final maximum has no context in which to be counted.

## Three Strands

The three grounds come from three separate sources: the first ground comes from the third axiom, the second from the Incommensuration Theorem, and the third from what an entropy is. The three grounds are like three strands of one rope, each strand spun from a different fiber. Each ground answers the old fear by itself. So the answer to the old fear depends on no single ground, as a rope of three strands still holds when one strand is cut.

## One End, and the Turn

Where does the new world begin? The new world begins at the end of the black holes' interiors, and all of those interiors share one end. Picture the interiors of the black holes as funnels. The interiors of different black holes stay distinct along their whole length, as funnels stay distinct along their walls. The interiors are joined at their ends because the ends cannot be told apart, and not because anything pulls the ends together. No signal from the end of any interior reaches the outside world, so no observer in our epoch can tell one end from another by any comparison. And the new world forms with no separate identity of its own, so no observer in the new epoch can tell, by any comparison, from which interior any part of the new world's content came. The principle that Chapter 6 set out applies to the ends of the interiors: "a difference that no comparison can register

is no difference". No comparison registers a difference between the end of one interior and the end of another, either before the end or after the end. So the ends are one.

The body carried away alone has a road of its own, because the lone body never falls into a black hole. Where the lone body is, the six small dimensions stop being held when nothing is left within the body's reach to compare against, as the body moves away from everything else. The content of the lone body does not cease either. I follow both roads to one place in my book *The View from Inside*: whichever exit a path takes, into a black hole or into emptiness, the end of the path is the turn. For the lone body, as for the body that falls, the large world has ceased to be anything to compare against, and on the far side of the turn the ten-dimensional geometry restores a large outside world.

The turn has two sides, and each side is a history that runs forward in its own time. On our side, the history of a falling body runs toward the limit, the end of the black hole's interior, and the description of that history holds up to the limit and not at the limit. On the new side, the history of the new world runs away from the limit as the new world's own time runs forward. When the new world's own observers trace that history backward, the history comes ever nearer the limit and does not reach the limit. Each history is like the marks of Chapter 6, set at half the distance to a line, then at half of what is left. The marks come ever nearer the line, and none of the marks lies on the line. Each history, like the marks, comes ever nearer the turn, and no moment of either history lies at the turn. No comparison registers the turn itself as an event, because to register the turn as an event a comparison would have to be made across the turn, a before compared with an after. Duration, temperature and rate belong to the approach on each side, and none of them belongs to the turn.

I identify the restoring of the outside world with the Big Bang of the new epoch. Every history of the universe is pieced together by observers from the light and the records that reach the present, as Chapter 1 said of everything we know of the past. The new epoch's observers piece together a history that runs back toward the turn. The observers find the beginning

of that history at the turn. So the Big Bang of the new epoch is the turn as the turn appears in the history that the new epoch's observers piece together.

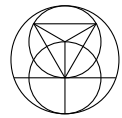
The cosmological constant is the energy of empty space that speeds up the expansion (Chapter 1). Could the cosmological constant keep the turn from coming? The cosmological constant cannot keep the turn from coming. The constant goes on carrying the galaxies apart in the space between the black holes, but the constant does not stop black holes from forming or the interiors from sharing one end, and inside the common end the constant has no effect at all. The condition that holds the six small dimensions depends on the large world around them, with things in it to compare against, and not on the constant. Because the end of one epoch is the beginning of the next epoch, the history of the universe is a cycle, and not a single arc from a Big Bang to a heat death.

## What This Means for You

The cold, dark sky that popular books describe is the true view of the far future from inside our epoch. You can stand on the step and know that the cold, dark sky is coming, over times far longer than the age of the universe so far. You can also know what comes after the dark sky, for three reasons: content needs a context, a featureless emptiness is never found, and every count of entropy belongs to the epoch in which the count is made. The dark sky is the last view of one epoch. On the far side of the turn a new epoch begins, with a new sky of its own.

**Key idea.** The long emptying of the sky is the modern form of the old fear of a heat death. But the long emptying is not the end. Three grounds show that the long emptying is not the end, and each ground is enough by itself. By the third axiom, content cannot be without a context, so a context forms again. A featureless emptiness would be perfectly symmetric and perfectly continuous at once, because it is everywhere the same and has no break, and the Incommensuration Theorem says that no observer finds both perfect at once by any comparison, so the emptying cannot come to rest. Entropy is a count made against a context, so when the context has emptied the count has nothing to be counted against. The interiors of all black holes share one end, the turn, and the next epoch begins from the turn. The emptying ends at the turn, and not in a final dark. The end of the emptying at the turn matters because the far future then leads on to a new epoch, and does not end in the dark.

What crosses the turn into the next epoch?



Chapter 9

# What Crosses Over, and What Stays Behind?

## The First Faint Pattern of the Next Sky

If the long emptying of the sky ends in a turn, what crosses over into the next epoch, and what stays behind? Go back once more to the back step on a clear night, and let the picture run far ahead. The smudges of the other galaxies have gone beyond the horizon. The horizon is the edge of what anyone on the step can ever see (Chapter 1). The stars over the step have gone out. What was left of the stars has ended inside black holes or drifted away alone. Chapter 8 showed that the dark sky of the far future is not where the story stops. The turn is the one end shared by the interiors of all the black holes of our epoch, and at the turn a new world with three large directions of space re-forms. In time the new world has a sky of its own.

Picture the first faint pattern of the new world's sky. The pattern is not a copy of our sky. The pattern shows none of our galaxies, none of our stars and nothing that was ever seen from our step. The pattern is nearly even in every direction, and across the pattern lies a very faint unevenness, of one kind everywhere, from which the galaxies of the next epoch will one day grow. Our own sky carries a pattern of the same kind, left by the epoch before ours. Our pattern lies in the afterglow of the Big Bang,

the warmth left over from the beginning of our universe (Chapter 1). Your eyes cannot see the pattern from the step, but radio telescopes have mapped the pattern across the whole sky.

I answer the question of what crosses and what stays behind in three parts. In this book the content is what a comparison finds: here, the matter and light of our epoch. First, the form of the content crosses the turn: what the matter of our epoch is, carried as one averaged form, with no mark of which black hole the matter came through. Second, the law returns: the structure of the world that I derive in this physics holds again on the far side of the turn, but the law is not carried across. Third, every count, every length and every record stays behind. Every thing stays behind as the thing it was. The faint pattern of the next sky is the form of the content, as the next epoch's comparisons register the form. I take the three parts one at a time, after a short history of a famous question about black holes.

## A Paper Sent from Pasadena

What survives a black hole is a question with a famous history. The physicist Stephen Hawking spent the academic year 1974 to 1975 as a visitor at the California Institute of Technology in Pasadena. Hawking had recently shown that a black hole gives off a faint glow and slowly evaporates, as Chapter 1 reported: a black hole that evaporates shrinks by its own glow until nothing of the hole is left. Hawking turned that year to the question of what the glow would mean for everything that had fallen into the hole. The physics journal *Physical Review D* received Hawking's paper, "Breakdown of predictability in gravitational collapse", on 25 August 1975. Gravitational collapse is matter falling in on itself under its own gravity, as when a black hole forms. The journal published the paper in November 1976.

Hawking's conclusion was stark. By his calculation the glow carries away the mass of the hole, and nothing in the glow records what went in. Hawking wrote, in the summary at the head of the paper, that "part of the information about the state of the system is lost down the hole". Hawking took the loss to mean "a fundamental limitation to our ability to predict the future", a limitation beyond the ordinary uncertainty of quantum theory. Hawking proposed a new rule for how the states of matter change, where a state is one complete arrangement of a thing's parts, and under the new rule some information is lost. Many physicists answered that the laws of quantum theory never destroy information. Physicists came to call the disagreement the information paradox. In 2005 Hawking published a second paper, "Information loss in black holes", in which he argued the other way: the making and evaporating of a black hole, taken as a whole, keeps the information.

In both papers Hawking asks one question: can the information that fell in be found again in our sky, in the glow? In this physics I first ask a question that comes before Hawking's question: which information is meant?

## Two Things Called Information

Think of a handwritten letter in a post office. The letter holds what it says: which words were chosen, in which order, out of all the words that could have been written. What the letter says belongs to the letter. The words go wherever the letter goes. A second thing belongs to the post office. The office's sorting machine reads only the postcode, so every letter in one bin looks the same to the machine, and the office can count how many different letters lie in each bin. The office makes the count with its own machine. If the office closes, its counts have nothing left to be counts for.

Physicists use the word *information* for both things, and in this physics I keep the two senses apart. In the first sense, information is the form of the content: what the matter is, and which alternatives the matter has taken. Information in the first sense is carried with the matter wherever the matter goes, as a letter's words go with the letter. In the second sense, information is a count of states relative to a context, like the office's count for one bin. A comparison, in this book, is the act of finding whether two things are the same or different, in some respect. Chapter 6 called what a comparison finds its content, and the respect in which the comparison finds the content, its context. Picture a thermometer that compares this morning's warmth with this evening's. The temperature that the thermometer finds is the content, and the two times of day are the context. For the counts in this chapter, the context is the outside world of an epoch: the sky and everything in the sky, against which the comparisons of that epoch are made.

Information in the second sense is the entropy of Chapters 7 and 8. An entropy is a count of the arrangements of a thing's parts that leave the thing looking the same from outside: the states that the comparisons available from a context cannot tell apart. In the post office, an entropy is the count in one bin: the letters are the arrangements. The sorting machine stands for the comparisons available from the context, because the machine cannot tell the letters apart. The entropy of a black hole is a count of the states of the hole's interior that no comparison from outside can tell apart. So the entropy of a black hole is a count made against the outside world as its context.

When the two senses are kept apart, a first result follows: information in the first sense is not destroyed in a black hole. Think of a road running across a map and off the edge of the paper. The road goes on past the edge of the paper, and the map simply stops describing the road at the edge. Physicists describe matter and space with two great descriptions. The quantum description is the physics of the very small, of matter and light. The smooth description of gravity is Einstein's theory, which treats space and time as smooth. Within the range where each description holds,

what the matter is passes whole from one moment to the next. Nothing of the matter's form is lost. Hawking's calculation showed a loss in one place only: where the falling matter met the *singularity*, the place at the edge of the range in which the smooth description of space and time holds. The loss in Hawking's calculation is like the road at the edge of the map, because the loss shows where a description stops, and no step inside either description removes the form of what fell in.

## What Stays Behind

Now carry the two senses to the turn, with one more picture. Think of a play performed again and again from one script. For each performance the crew builds a new stage, sets out props, counts the audience and measures the floor. When a performance ends, the crew strikes the stage: the crew takes the stage down and keeps nothing that was on the stage. In the picture, the stage stands for the outside world of an epoch, with its lengths, clocks, counts and things.

First, the counts stay behind. Chapter 8 showed that the outside world of the old epoch empties, and Chapter 6 showed that at the end of an interior the outside world has no moment at all. No signal from the end of an interior ever reaches the outside, so nothing in the outside world can place the end before, at or after any moment of the outside world's time. So at the end there is no old sky and no old observer against which anything can be compared. Every count in the second sense was made against the old outside world, as the office's counts were made with its machine. Once the office has closed, no count goes forward. No entropy crosses the turn, for the matter or for space itself, because each entropy was counted against the context that has ended. In the new epoch every count is made against the new context and starts from the new epoch's own start, as the crew of a new performance counts its own audience.

Second, the lengths stay behind. The new world re-forms from the ten-dimensional geometry. The ten-dimensional geometry is the geometry of all ten dimensions of the world. Chapter 8 showed that the new world had no separate identity in the ten-dimensional geometry, so the new world has no past of its own. The crew builds each new stage without measuring the old floor, because nobody carries a tape measure from one stage to the next, and in the same way the new world takes on no size from the old world.

Third, the records stay behind. A record is a mark that sets one part of a world apart from another part: an inscription, a scar, a footprint, a lump of matter in one place and not another. The new world inherits no record from the old world, for the same reason that the new world inherits no length: the new world has no past of its own.

Fourth, two things stay behind: the shape of the old large space, and the fields of its matter. Our three large dimensions of space have bends and lumps, and our matter is made of fields. Neither the bends and lumps nor the fields pass through the turn as that shape or as those fields. The six small dimensions are a different case. The six are six further directions at every point of space, curled up far smaller than the core of an atom (Chapter 4). The six come back with the same shape in every epoch, because the same law holds the six at that shape again. The return of the six belongs to the law, and I take up the law last.

Put the four together: the counts, the lengths, the records, and the shape of space with the fields of matter. Then every thing stays behind as the thing it was. Take a star, a planet, a book or a body: each has a definite form of matter, with a size in a geometry, made of fields, and set apart from other things by marks. The six small dimensions are held at their shape while the large world of space and time is around them, with things in it to compare against (Chapter 8). Chapter 5 showed that the forms of matter end where the hold on the six ends, so none of the forms crosses. The old sky stays behind entire, with everything that was ever seen from the back step.

## What Crosses

The content itself crosses the turn and does not stay behind. Chapter 8 set out the third axiom of this physics: there is no content without a context in which it is content. The content does not cease at the end of an interior, and so a new context forms around the content. The content is carried from the collapse on one side of the turn to the new world on the other side, and the form of the content is carried with the content. The form of the content is information in the first sense.

The form of the content crosses as one form. Each black hole of our epoch took in its own matter, so each interior carries the form of its own content. Chapter 6 stated a principle that applies to the many forms at the turn: a difference that no comparison can register is no difference, because every distinction is made by comparison. Someone could tell one interior's form from another's only by comparing the two forms side by side, in a context that draws the difference. The old outside world was the only context that ever drew the differences between the interiors, and at the end of the interiors the old outside world has no moment at all. So no comparison can register a difference between the forms of the interiors, and by the principle of Chapter 6 the forms are one. The form of the content passes as one form, with no mark of which black hole the content came through.

Think of a crowd in a great stadium, heard from a hill a mile away. You hear one roar, rising and falling. You cannot pick out any one voice in the roar, yet every voice in the stadium goes into the roar. The voices are like the distinctions of the old epoch, and the roar is like the one averaged form. In the same way the distinctions of the old epoch survive the turn "averaged and not erased", in the words of *The Gravitational Passage*, another book of this collection.

A body carried away alone reaches the turn by the other road, as Chapter 8 showed: the body never falls into a black hole, and the expansion carries the body beyond the reach of all other matter. For the lone

body, too, the large world stops being anything to compare against, and the hold on the six small dimensions ends. The matter of the lone body stops being matter of our epoch's form. But the content of the lone body does not cease, so a context forms again for that content, as for all content. In the books of this collection I follow the form of the content that ends inside the black holes all the way into the one averaged form of the new sky. For the body carried away alone, I follow the form of its content to the turn.

In this physics Hawking's question has an answer. When information in the first sense falls into a black hole, the information is not destroyed: the information is carried with the content to the turn, and the information reappears at the beginning of the next epoch. The information cannot be found again in our sky. Nothing of the information reaches the outside while the hole lasts. A black hole formed from a star lasts far longer than the outside world of its epoch, as Chapter 1 reported. A black hole of the Sun's mass glows itself away in about two times ten to the sixty-six years, and the sky beyond our own group of galaxies empties in a hundred billion to a trillion years. So for every hole formed from a star, what fell in is out of reach of our sky, and is kept.

## The Faint Pattern

What does the form of the content look like when the form arrives? For our own epoch, astronomers have measured the answer. The oldest light that reaches us is the afterglow of the Big Bang, the microwave background of Chapter 1. The afterglow was released when the first atoms formed. The expansion of the universe has stretched the afterglow into microwaves about a millimeter or two long. In September 1992 the physicist George Smoot and his colleagues reported that the afterglow is not perfectly even, using the maps made by the satellite called the Cosmic Background Explorer (COBE). The temperature of the afterglow differs from place to place by about one part in a hundred thousand of its tem-

perature. Every later map has shown the same faint pattern in finer detail, among them the maps of the satellite named after the physicist Max Planck.

The small differences are called the *departures from uniformity*: the faint differences of density with which an epoch begins, and from which, by gravity, the galaxies of the epoch later grow. I identify the departures from uniformity with the form of the content carried through the turn: the distinctions of the epoch before ours, averaged.

The new world could never begin perfectly even. Symmetry is staying the same through a change, as a law that holds in every city stays the same from city to city. Continuity is having no break, as a ramp rises with no sudden step. The Incommensuration Theorem, which Chapter 8 stated, is a structural fact about the nature of knowing: no comparison finds perfect symmetry and perfect continuity together. If a world were exactly the same at every place and in every direction, the world would be perfectly symmetric and perfectly continuous. So the new world begins with small departures. The small departures are the old distinctions, carried as one averaged form.

The form of the content crosses as one form, so the departures that the form leaves carry two marks, and astronomers have looked for both. The first mark is a pattern joined across the whole sky. Some regions of the sky are so far apart that no signal has ever passed between them, and yet those regions show the same temperature, and a pattern of the same kind. The pattern also has nearly the same strength on large sizes as on small ones. If the form crossed as separate pieces, one for each black hole, the pattern would fade away on the largest sizes. The measured pattern does not fade. The second mark is that every ingredient of a new world departs from evenness together: its matter, its dark matter and its light. The Planck maps show no separate pattern belonging to one ingredient alone. The maps limit a pattern of that kind to less than about two percent of the whole.

The first faint pattern of the next sky will be the averaged form of the content of everything that falls into the black holes of our epoch. If a part of the world seen from the back step ends inside a black hole, that part adds its share to the one form, as one voice adds to the roar. No one in the next epoch will pick out our share. Our share is there all the same, a part of the unevenness from which the galaxies of the next epoch grow.

## What Returns

Go back to the play. When the crew strikes the stage and builds a new stage for the next performance, one thing comes back every time: the script.

In the picture, the script stands for the law: the structure of the world that I derive in this physics. The law returns in every epoch without being carried across the turn: the law holds again on the far side, as the same script is played again on a new stage. The world has ten dimensions in every epoch: one of time, three large dimensions of space, and the six small dimensions of Chapter 4. The six have the same shape in every epoch, and the six are held at the same size in units of the Planck length, the length at which gravity and the quantum meet on equal terms. At the Planck length the effects of gravity and the effects of quantum physics are equally strong. So every epoch has the same one vacuum, the settled state of empty space that Chapter 4 described. A count made against the old outside world is a different kind of thing from the law, the ten dimensions or the one vacuum. So the law, the dimensions and the vacuum stay unchanged when every count starts afresh at the turn.

Do the constants of nature (the fixed numbers in the laws of physics) change from one epoch to the next? The answer has three parts: the law, the strength of gravity, and the measured proportions of matter.

The first part is the law, which is the same in every epoch.

The second part is the strength of gravity. In this physics I take the strength of gravity from measurement. The strength of gravity sets the Planck length, together with the speed of light and with Planck's constant, the number that sets the size of the smallest steps in which matter and light trade energy. The Planck length is the ruler of this physics: the size of the six is held at a fixed number of Planck lengths, and every other length can be read against the Planck length. Is the ruler of the next epoch the same length as ours? To find out, someone would have to lay our ruler beside the ruler of the next epoch. Think of two towns, each with its own yardstick, that never meet and never trade. Within each town every length is read against the town's own yardstick, and nobody can ever lay one town's yardstick beside the other's. The turn is like the gap between the two towns: no comparison is ever made across the turn, so no one ever lays our ruler beside the ruler of the next epoch. So in this physics I assign the strength of gravity no value in another epoch.

The third part is the measured proportions of matter. Everything that anyone in any epoch measures is a ratio, such as the mass of a proton set against the mass of an electron, read within that one epoch. No one ever sets a measured number of our epoch beside a measured number of the next, as with the two towns' yardsticks.

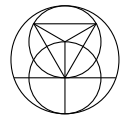
In 1992 the physicist Lee Smolin proposed a different picture, in a paper titled "Did the universe evolve?". In Smolin's picture each black hole gives rise to a new universe, whose basic numbers differ slightly from the numbers of its parent universe. Over many generations, universes that make many black holes come to outnumber the rest, in the way natural selection acts on living things. Smolin's picture and this physics agree that black holes lead to new beginnings. But in this physics all the interiors of an epoch share one end, so all the black holes of an epoch together give rise to one next epoch. So the epochs follow one another in a single line, with no branching family of universes for selection to act on. The law holds again in each epoch.

## What This Means for You

Whatever of you ends inside a black hole is kept, as a share of the averaged form from which the next epoch's galaxies grow. Nothing of you crosses as you. Chapter 6 showed that, in the far future, the matter of your body, of your house and of every star you can see from the step will end inside black holes or drift away alone. Our own microwave sky carries a faint pattern. The pattern is the averaged form of the content of everything that the black holes of the epoch before ours took in. The galaxies you count from the step grew from that pattern.

> **Key idea.** Information has two senses: the form of the content, which goes wherever the matter goes, and a count of states, which is always a count made against some context. At the turn the old context has no moment, so no count, no entropy, no length, no record, no shape of the old large space and no field crosses, and no thing crosses as the thing it was. The form of the content crosses as one averaged form, with no mark of which black hole the content came through. Comparisons in the next epoch register the averaged form as the departures from uniformity: the faint pattern from which the galaxies of the next epoch grow. The law returns: the same law holds again on the far side, and the law is not carried across. The form of the content crosses, and nothing crosses as itself. The crossing of the form is important because the end of our sky destroys nothing of what the matter of our sky is: the next sky begins from the averaged form of the content that fell into the black holes of our epoch, under the same law.

If the form of the content crosses, could someone send something across the turn on purpose: a traveler, a vessel, or a message meant to be read?



Chapter 10

# Could Anyone Escape?

## Stepping Off the Step

Could anyone escape the end of our epoch, the era of the world whose history runs back to the Big Bang, by traveling into another universe, or at least by sending a message across? Stand on the back step once more and ask the question plainly. Could you step off the back step into another sky: a younger, warmer sky, full of new stars, where the long emptying of the sky, as the galaxies pass beyond the horizon and the stars go out, has not yet begun? The turn is the one end shared by the interiors of all the black holes of an epoch. The next epoch begins from the turn. Chapter 9 showed that the form of the content (what the matter of our epoch is, and which alternatives the matter has taken) crosses the turn as one averaged form, and that the same law (the structure of the world that I derive in this physics) holds again on the far side of the turn. The question now is whether anything can cross on purpose, as itself, and be there on the other side to use what it brought.

The answer that this physics gives is short. Nothing escapes as itself: no body, no vessel, no readable message and no person crosses from our epoch into the next epoch. And there is no other universe that a journey could reach. A path is a route for a traveler or a signal. No path joins the

next epoch to ours. Any place a path from here can reach belongs to our own world. I set out the reasons in the rest of this chapter. I also set the best published plan of escape beside the reasons.

## A Bridge Between Two Sheets

The idea of a passage to somewhere else began with a paper about particles: a passage through space and time. In the spring of 1935 the physicist Albert Einstein was working at the Institute for Advanced Study in Princeton. Einstein's young assistant was Nathan Rosen. Einstein wanted a picture of particles in which nothing became infinite. In the picture Einstein wanted, no particle would have a point of infinite density at its center. On 8 May 1935 the journal *Physical Review* received the paper of Einstein and Rosen, "The particle problem in the general theory of relativity". In the paper Einstein and Rosen represent space, in their words, as "a space of two identical sheets, a particle being represented by a 'bridge' connecting these sheets".

Einstein and Rosen meant the bridge as a model of a particle, and not as a road for a traveler. Later physicists read the geometry of Einstein and Rosen another way: as a short tunnel joining two regions of space. Physicists call a short tunnel of that shape a *wormhole*: a shape of space and time, allowed by Einstein's equations, in which a short passage joins two places that are otherwise far apart.

Half a century later physicists returned to the tunnel because of a novel. Michael Morris and Kip Thorne were physicists at the California Institute of Technology. In May 1988 Morris and Thorne published a paper in the *American Journal of Physics*. The title of the paper was "Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity". Morris and Thorne tie the question of their paper to a novel, *Contact*, by the astronomer Carl Sagan. In Sagan's novel, travelers cross our galaxy through a wormhole. Morris and Thorne explained why a black hole, or the bridge of Einstein and Rosen, would not serve as a road

for a traveler. Then Morris and Thorne found a new family of wormholes through which a traveler could, in principle, pass. Each wormhole of the new family has a *throat*, the narrowest part of the tunnel, and the throat must be held open by a material whose tension (a pull, like the pull of a stretched rubber band) is greater than the material's energy. No one has ever found a material whose tension is greater than its energy.

A larger hope has run through popular books on the far future. The hope is that a wormhole might lead out of a universe that is running down, into another universe.

## Kaku's Plan of Escape

The physicist Michio Kaku gives the fullest plan of escape in any popular book, in his book *Parallel Worlds* (2005), and Kaku's plan deserves to be told in Kaku's own terms first.

Kaku holds that our universe is dying. In Kaku's account the expansion of our universe speeds up, the stars burn out, and the temperature falls toward a floor, a lowest level at which no machine can work and no thought can run. Kaku takes the floor from the work of the physicists Lawrence Krauss and Glenn Starkman, which Chapter 7 described. Kaku defines death by what a mind does: "Death can be defined as the final cessation of all information processing". So, on Kaku's account, any civilization that understands the laws of physics must one day face the death of its universe.

In Chapter 11 of *Parallel Worlds*, "Escaping the Universe", Kaku asks whether a civilization facing the death of its universe could leave the universe. Kaku is careful about exactly what he asks. "Physicists want a 'proof of principle'", he writes: by a proof of principle Kaku means a demonstration that, with technology advanced enough, the laws of physics would allow an escape into another universe. Kaku leaves the question of whether the resources for an escape exist to civilizations billions of years from now.

Kaku then lays out eleven steps. First, a civilization completes a theory of everything: one theory joining gravity and the quantum. The civilization uses the theory to learn whether wormholes are stable. The civilization searches the sky for wormholes left over from the beginning of our universe. The civilization also searches for *white holes*: a white hole is the time reverse of a black hole, a black hole run backward in time, which would throw out what a black hole takes in. The civilization sends shielded probes through a black hole. Then the civilization builds a black hole slowly, by herding neutron stars together. The civilization builds the black hole to study the passage that Kaku hopes lies at the center of a spinning black hole. The civilization tries to make a *baby universe*: a tiny region squeezed and heated until the region swells into a universe of its own, joined to our universe by a wormhole "like an umbilical cord". The civilization builds atom smashers the size of a solar system. The civilization also builds banks of lasers spread across many star systems, all firing inward on one point. The civilization uses the atom smashers and the lasers to reach the energies at which, Kaku says, space and time become unstable, so that a wormhole forms "connecting our dying universe with a much younger, much hotter universe".

In the next steps of Kaku's plan the civilization travels between the stars by a *warp drive*, a ship that would shrink the space ahead of it and stretch the space behind it. Kaku notes that a warp drive "cannot be used to leave the universe", but he holds that a warp drive can help to build the machines that might be used to leave. The civilization would use *cosmic strings* in one of the machines for leaving the universe. Cosmic strings are thin threads of concentrated energy that, Kaku says, the early universe may have left stretched across space. Cosmic strings are a different thing from the tiny strings of string theory. Kaku reports, following the physicist J. Richard Gott, that two cosmic strings rushing past each other might carry a civilization back into the civilization's own past, "when its universe was much warmer". The civilization gathers *negative energy*, a state of a field with less energy than empty space. The civilization needs negat-

ive energy to hold a wormhole open. And the slowed, hibernating minds of the civilization wait for a passage to another universe to open by chance.

Kaku calls the eleventh step "The Last Hope". Suppose every passage that can be made is far too small, or too violent, for any body to survive. In that case, Kaku writes, future intelligence would have "but one remaining option: to inject enough information into a new universe to recreate our civilization on the other side of the wormhole". The civilization would send a seed, as an oak sends an acorn. The seed would be a microscopic device, or a coded beam, carrying everything needed to rebuild the civilization. On the far side of the wormhole the seed would build a tiny machine. The tiny machine would find a planet and build a laboratory. The laboratory would then grow new people and place in the brains of the new people "the memory and personality of the original human". Kaku grants that every step reads like science fiction. Yet Kaku holds that "there is nothing in the laws of physics or biology to prevent this from occurring".

Kaku's plan needs four things of the universe on the other side of the passage, across all eleven steps of the plan. The other universe must be worked out in advance, so that the travelers know what they will find there. The other universe must be younger and warmer than our dying universe. The other universe must supply the raw materials for rebuilding the civilization, because the seed carries only information. And if a gateway opens by chance, the other universe may be unknown at the moment of passage.

Kaku's plan is bold, and Kaku takes the far future seriously. Kaku's plan depends on three things being true: that the universe ends in a final cold dark, that there is another universe a passage can reach, and that something of us, a body, a seed or at least a message, can cross as itself. I give the answer of this physics on each of the three things in turn.

## An Epoch That Turns, Not a Universe That Dies

I gave the first answer in Chapter 8: the universe does not end in a final cold dark. In this physics the long emptying of the sky ends in a turn, and not in a final dark. Every epoch makes structure, such as galaxies, stars and black holes. A bound structure is a structure held together by its own gravity. Each bound structure ends inside a black hole or is carried away alone, beyond the reach of all other matter, and the interiors of all the black holes reach one end. Both endings lead to the turn, and the next epoch begins from the turn.

Kaku takes the speeding up of the expansion as the sentence of death for our universe. In this physics the speeding up of the expansion belongs to the outside world of one epoch: the whole of what can ever reach an observer in that epoch, every star, galaxy and glow whose light arrives, now or later. The cosmological constant drives the speeding up, and the cosmological constant is the energy of empty space that Chapter 1 introduced. In Chapter 2 I identified the cosmological constant with the part of the energy of empty space that a measurement made from inside the universe can take in. A measurement made from inside the universe is made in the outside world of an epoch. At the shared end of the interiors there is no outside world in which any measurement could be made, so at the shared end the cosmological constant acts as nothing at all. So the faster expansion does not stop black holes from forming or from merging. And the faster expansion does not stop the epoch from turning into the next epoch. What ends is the sky of one epoch, and what follows the sky of one epoch is another epoch, under the same law.

## What Reaches the Turn

Now follow a traveler who sets out to cross from our epoch into the next epoch. Chapter 6 showed that every observer's road through time has two possible ends, and no third end. Either the traveler falls into a black hole and reaches the end of the black hole's interior, or the traveler is carried away alone, with nothing left to compare against except the traveler's own horizon, the edge of what the traveler can ever see.

Take the first ending, inside a black hole. Inside the horizon of a black hole, the direction toward the center is the direction of time. On the traveler's own clock the end of the interior comes after a finite time: for a black hole of the Sun's mass, at most about fifteen millionths of a second after the traveler crosses the horizon. The end of the interior is a limit, where the smooth description of space and time (Einstein's theory of gravity) reaches the edge of the range in which the smooth description holds. No clock at the end of the interior records a last tick (Chapter 6). The end lies at no moment of the outside world's time.

The six small dimensions are six further directions at every point of space, curled up far smaller than the core of an atom (Chapter 4). The six small dimensions are held at their shape while a large world is around them, with things in it to compare against. In both endings the hold on the six small dimensions ends. The hold ends because the large world is no longer there, with things in it to compare against. Chapter 5 showed that the forms of matter (atoms, stars and bodies) last only while the hold on the six small dimensions lasts, so in both endings the matter of the traveler stops being matter in the form that our epoch gives matter. The content itself does not cease. In this book the content is what a comparison finds, and in the traveler's case the content is the traveler's matter. But the form of matter does not last, and the form of matter is what makes a body a body.

Chapter 9 showed that at the turn itself no length crosses, no shape of the old large space crosses, and no field of matter crosses. A body is matter in our epoch's form, made of fields, with a size in a geometry. So no body crosses the turn as a body, whether the body is an astronaut in a shielded craft, a probe, a seed, or the tiny machine of Kaku's last hope.

## No Message, No Record, No Identity

Suppose, then, that the traveler sends information instead of a body, as Kaku proposes in his last hope. Recall the handwritten letter in the post office of Chapter 9, and the office's sorting machine. What the letter says is information in the first sense: the form of the content. The office makes counts with its own sorting machine, and the counts are information in the second sense: counts made against a context, the respect in which a comparison finds what it finds.

In the first sense, something of Kaku's seed does cross the turn: the form of the seed's content. If the seed falls into a black hole, the form of the seed's content is not destroyed. The form of the seed's content is carried to the turn. At the turn the form of the seed's content joins the one averaged form from which the galaxies of the next epoch grow, as one voice joins the roar of the crowd in a stadium (Chapter 9). In the picture, the form of the seed's content is the one voice, and the one averaged form is the roar. So something of every message dropped into a black hole reaches the next epoch.

As a message, the seed does not cross. A message is a record: marks drawn in our world, made to be read by a reader who can tell the marks apart. The new world inherits no record and no mark from the old world. The context of the new world draws none of the distinctions of the old world. In this physics a thing is real when the thing is given in an actual act of comparison, here and now (Chapter 7). No act of comparison spans the turn, so no finding made in our epoch is real in the next epoch, and no record of our epoch is ever set beside a record of the next epoch. The form

of the message arrives as a share of one averaged form, with no mark of which black hole the message came through, and no mark of who wrote the message. So the form of the message arrives as no message, because no mark arrives to be read. And the form of the message arrives as the instructions of no one.

Identity does not cross the turn either. Someone could find that a thing in the next epoch is the same person, or the same civilization, or the same message, as a thing in our epoch, only by comparing the two things across the context of our epoch and the context of the next epoch. No one ever makes a comparison across the context of our epoch and the context of the next epoch, because no comparison spans the turn, so nothing in the next epoch is the same thing as anything in our epoch, by any finding that anyone could make.

And the people of Kaku's last hope would not be in the seed in any case. Kaku imagines travelers "merging carbon with silicon and reducing their consciousness down to pure information". Picture a smooth ramp poured in concrete, and beside the ramp a staircase of identical tiles laid to follow the ramp. However small the tiles are made, the staircase always has seams, and the ramp has none. A computation is one rule applied the same way, step after step. A computation is like the staircase: identical steps, each separate from the next, the same kind of step every time. I identify the first-person stance, the inside of a life, with the ramp: one unbroken run that goes one way and sets this moment apart from every other moment. A computation made perfect as a computation would make the sameness of its steps perfect. To be the inside of a life as well, the computation would also have to be perfectly unbroken. In Chapter 8 I stated the Incommensuration Theorem, a structural fact about the nature of knowing: at the foundation of any comparison, symmetry (staying the same through a change) and continuity (having no break) cannot both be perfect together. Perfect sameness of steps is perfect symmetry, and being perfectly unbroken is perfect continuity. So, by the Incommensuration Theorem, no computation is perfect sameness and perfect unbrokenness together. *What Cannot Be* is my book, in this collection, on the limits of

computation. In *What Cannot Be* I write: “A person is not a very large file”. When a device carries a description of a person, the device carries a map of the person, and the person is not in the map.

## No Other Sky Along Any Path

The second thing that Kaku’s plan needs is another universe that a passage can reach: a place to go. By “another universe” Kaku means a place that a passage could reach. In this physics there is no other universe that a passage could reach. I give three reasons that no passage could reach another universe, and each of the three reasons comes from a different source.

The first reason comes from the turn. The next epoch begins at the shared end of the interiors of the black holes. No signal from the end of an interior reaches any moment of the outside world, so the end of an interior lies at no moment of our time, earlier, now or later. No path runs from any place in our epoch to any place in the next epoch. Two things join the two epochs. The law holds again in each epoch, and the one averaged form of the content crosses the turn. No act of comparison and no path join our epoch to the next epoch.

The second reason comes from what a place is. Think of a country where the only way to travel is by road, and call the country the road country. For a traveler in the road country, a town is a place because roads join the town to other towns, and a town that no road reaches is no place at all, however good the traveler’s car might be. In this physics, space is the pattern of which events a signal can join: in the picture, the towns stand for events, and the roads stand for the paths along which a signal can go. So if a path from here reaches a region, the region is a part of our own pattern, and so a part of our world, whether the path goes through a wormhole, a warp drive or anything else. And if no path from here can reach a region, the region has no position in our pattern, so relative to us the region is no place at all. A journey to another universe therefore has

one of two results, and neither result is another universe. If the journey arrives, the journey arrives somewhere in our own world. If nothing can arrive, there is nowhere to go.

The third reason does not depend on the turn at all. I call a whole world within which comparisons can be made a *domain*. Picture a house that holds every world as one of the house's rooms. To hold all the worlds as one whole, the house must do two things. First, the house must count every room as a room of the house in the same sense, with one way of belonging shared by all the rooms, and counting every room in the same sense is sameness. Second, the house must join every room to every other room, with no room cut off from the rest of the house, and joining all the rooms in that way is unbrokenness. The house would have to make both sameness and unbrokenness perfect in the one comparison by which the house holds the rooms together. The Incommensuration Theorem says that, at the foundation of any comparison, symmetry and continuity cannot both be perfect together. Sameness is symmetry and unbrokenness is continuity, so no domain contains every domain. The epochs are not rooms of one larger house, with doors between the rooms for a traveler to open. Each epoch is a whole world, complete from inside, and the series of epochs is a series of worlds under the same law. The epochs before ours and after ours are worlds, and each epoch is real in its own acts of comparison. No act of comparison is real in two epochs. No journey links any two epochs.

## The Plan, Step by Step

Go back to the road country, where the only way to travel is by road. In the road country, each of Kaku's steps is a new way to travel. The first way digs down through the ground, the second builds new roads and faster cars, the third tries the road back to the past, the fourth waits by the road-

side, the fifth asks for a better map, and the last sends a letter instead of a traveler. Take the ways in that order, and for each way this chapter has already given the answer.

The first way digs down, through a black hole. Kaku would send probes through a black hole, then build a black hole slowly, and Kaku hopes that a spinning black hole holds a passage at the center of the black hole. This physics agrees with Kaku that a traveler crosses the horizon of a black hole one way only, and that nothing returns across the horizon. A probe or a traveler reaches the end of the interior, the one end shared by all the interiors, and at that end the matter of the probe or of the traveler stops being matter of our epoch's form. In *The Gravitational Passage*, another book of this collection, I report that the matter falling in while a real black hole forms breaks up the inner passage of a spinning black hole. In *The Gravitational Passage* I also expect the inside of a real spinning black hole to end as every interior ends. Kaku hopes to find a white hole at the far end of a black hole, and the counterpart of Kaku's white hole in this physics is the beginning of a whole new epoch, taken as one beginning. The beginning of a new epoch is not a region of space at the far end of any one black hole. So the way down through a black hole leads to the turn, where no body arrives as a body.

The second way builds new roads and faster cars: the baby universe, the machines of the Planck scale, negative energy and the warp drive. Kaku's baby universe begins as a false vacuum (Chapter 4). A false vacuum is a state of empty space that could fall to a lower state. This physics has one vacuum, one settled state of empty space, and no second held state beyond the one vacuum, so a bubble made by a civilization has no other world to open into. In this physics the six small dimensions contain the range of what a comparison could find: the possibilities that matter can take. A comparison is made across space, from here to there, and no comparison is made across possibility. So there is no larger space in which a new universe could bud off and stay joined to our universe by a cord. Kaku's civilization builds its machines to reach the energy of the Planck scale. Chapter 2 introduced the Planck scale: the scale at which gravity

and the quantum meet on equal terms. At the Planck scale the smooth description of gravity and the quantum description both reach the edge of the range in which each description holds, and neither description takes over from the other. No other world lies beyond the edge of the two descriptions. In the road country, a wormhole held open by negative energy would be a new road, and a warp drive would be a faster car. Wherever a new road or a faster car arrives, the new road or the faster car arrives at a town on our own roads. So the wormhole and the warp drive are each a road within our world, and not a road out of our world.

The third way tries the road back to the past. Kaku hopes that Gott's cosmic strings might carry a civilization back to the time when the civilization's universe was warmer. Picture a traveler in the road country who drives back to the town where she was born. The traveler arrives, and she finds the town as the town is on the day she arrives, and not as the town was on the morning when she was born. Chapter 6 gave the reason, which holds for every journey: every comparison runs one way, and what each comparison finds is laid down as a record, in an order that cannot be reversed. So wherever a traveler arrives, the arrival is a new finding of the traveler's own, made after every finding the traveler made before. The warm past was found as the time it was by the people who lived then, and the traveler does not reach the warm past as the time it was.

The fourth way waits by the roadside. Kaku's slowed minds wait for a gateway to open by chance. In this physics the waiting minds come to the end of the epoch. Either the waiting minds fall into a black hole and reach the shared end of the interiors, or the waiting minds drift away alone. In both endings the matter of the waiting minds stops being matter of our epoch's form.

The fifth way asks for a better map: the theory of everything. Kaku wants the theory of everything in order to work out whether a wormhole to another universe would be stable. A better map of the roads draws every road more exactly, and a better map draws no road that is not there. Whatever the theory of everything found, the reasons already given in this chapter would still be true: every place that a wormhole joins lies in

our own world, no path joins the next epoch to ours, and nothing returns across a horizon. So no calculation with the theory of everything shows a road to the next epoch.

The last way sends a letter instead of a traveler: the seed of Kaku's last hope. For the seed, the answer comes from the letter in the post office of Chapter 9. If the seed falls into a black hole, the form of the seed's content crosses the turn as a share of the one averaged form. The seed does not cross as a message, the tiny machine does not last as matter, and the memories and personalities written into the seed are descriptions of persons, and not persons.

The answers already given also apply to Kaku's four conditions on the other side. The first condition is that the other side must be worked out in advance: the law of the next epoch is the law of our epoch, and this physics says so, but no particular thing of the next epoch can be worked out from our epoch. The second condition is that the other side must be younger and warmer: the next epoch does begin hot, at no moment of our time. The third condition is that the other side must supply the materials: the next epoch makes its own matter, at and after the turn from which the next epoch begins. The fourth condition is that the other side may be unknown at the moment of passage: in this physics no passage to the next epoch is made, so there is no moment of passage.

## The Cosmic Egg

Kaku ends his account of the last hope with a picture. In Kaku's picture the seed would be a "cosmic egg", holding the whole information of a civilization. The materials for rebuilding the civilization would wait on the other side.

This physics has a cosmic egg too, and the cosmic egg of this physics is larger than Kaku's egg. When things end inside the black holes of an epoch, the content of all those things crosses the turn as one averaged form. The one averaged form is the seed of the next epoch's structure: the

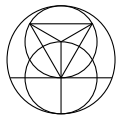
faint pattern from which the galaxies, the stars and, in time, the watchers of the next epoch grow. The one averaged form carries the form of the content of everything that fell in, and the instructions of no one. The next epoch grows by the same law that our epoch grew by.

## What This Means for You

In this physics the future is the next epoch, which comes from the end of our epoch by the same law. The future needs no rescue from the dark. Whatever part of our world falls into a black hole adds its share to the seed of the next world. No plan of escape, however advanced, will carry you, your civilization or your message out of our epoch, each as itself. Every place you could ever travel to, by any engine, is a part of our own world. The sky over the back step is the only sky that any journey from here will ever reach.

> **Key idea.** Kaku's plan of escape needs a dying universe, another universe a passage can reach, and something of us that crosses as itself. In this physics our epoch turns into the next epoch instead of dying. No body, record, identity or person crosses the turn. The form of the content crosses as one averaged form, which arrives as no message and as the instructions of no one. No path joins the next epoch to ours, and any place that a path can reach is part of our own world. Nothing escapes as itself, and there is no other universe that a journey could reach. The answer matters because the far future needs no escape: what comes after our sky is the next epoch, under the same law, seeded by the form of the content of our own epoch.

If each epoch comes from the end of the epoch before it, under the same law, have the emptying and the new beginning happened before?



Chapter 11

# Has This Happened Before?

## The Sky Has Done This Before

Has the whole story of this book, the long emptying of the sky and the turn at the end of the emptying, happened before? Yes. Our epoch began from the end of the epoch before ours. The epoch before ours began from the end of an epoch earlier still. The turn is the limit at which the interiors of all the black holes of an epoch end (Chapter 8), and the next epoch begins from the turn. No turn in the cycle of epochs is the first turn.

Stand on the back step on a clear night once more. The faint smudges you count are the galaxies of our epoch. Behind the galaxies lies the microwave background, the faintest light of all. The microwave background is the glow left over from the early years of our epoch. In this physics, our epoch began at the turn at which the epoch before ours ended. Before our sky there was another sky. The earlier sky filled with galaxies, thinned and emptied, as Chapter 1 showed that our own sky will. The sky you are looking at began from the end of the earlier sky. The sky over the step has filled and emptied before.

Other physicists have described cycles of the universe too. Each of those physicists describes how one history of the universe gives way to the next history. I describe each physicist's cycle in its own terms first. Then I set each of those cycles beside the cycle of this book. The cycles of

the other physicists share a great deal with the cycle of this book. The cycles differ from the cycle of this book in two things: in the place where one history gives way to the next, and in what the change from one history to the next needs.

## A Cycle With No First Turn

I tell the cycle of this book first, once and in full. In Chapter 1 I defined an epoch as one era of the world, in which stars, galaxies and black holes form. Every bound structure of an epoch ends in one of two ways. The structure (a star or a galaxy, for example) ends inside a black hole, or the structure is carried away alone. To be carried away alone is to be carried by the expansion beyond the reach of all other matter. On the clock of a body that falls into a black hole, the end of the black hole's interior comes after a finite time. The end of the interior is a limit: the smooth description of space and time holds up to the end and not at the end, and the end lies at no moment of the outside world's time. No signal from the end of an interior ever reaches the outside world, so nothing in the outside world can place the end before, at or after any moment of the outside world's time. All the black hole interiors of an epoch share one end, because no observer can tell the end of one interior from the end of another by any comparison. I state the principle in my book *At the Edge of Reality*: "a difference that no comparison can register is no difference".

The six small dimensions are six further directions that every point of space carries, curled up far smaller than the core of an atom (Chapter 4), and the six small dimensions are held small while the large world of space and time is there around the six, with things in the large world to compare against (Chapter 8). At the shared end of the interiors the outside world has no moment, so at that end no outside world is around the six small dimensions to hold the six small. In Chapter 8 I pictured what follows with a seesaw, with the three directions of space on one end of the seesaw and the six small dimensions on the other end. As the end of an

interior comes near, the six small dimensions grow while the three directions of space shrink. In the new world the seesaw tips back. The geometry of all ten dimensions restores a large world with three large directions of space. The restored large world is the next epoch. The turn is the limit between the old world and the new. The turn is a limit approached from both sides and reached from neither. So the turn is not an event in time. In Chapter 8 I identified the Big Bang of our own history with the turn, as the turn appears in our history when observers inside our epoch trace our history back.

The turns between successive epochs are distinct turns. A ship's logbook gives a picture of why the turns are distinct. The logbook records the port the voyage set out from, and the logbook holds no entry written at the voyage's own end, since every entry is written before the voyage ends. The comparisons made inside an epoch are like the entries in the logbook, and the epoch is like the voyage. The comparisons of an epoch register the turn that the epoch came from, as the logbook records the port. When the observers of an epoch trace the history of the epoch back, the observers find the turn the epoch came from as the beginning of that history. The comparisons of an epoch do not register the turn at which the epoch's own black hole interiors end, as the logbook holds no entry written at the end of the voyage. The comparisons of an epoch end at the turn at the end of the epoch. No comparison of the epoch is made at that turn or across that turn. The epochs follow one another in a single line, and do not form a branching tree of universes, because the interiors of each epoch share one end and the turns of successive epochs are distinct.

The cycle of epochs has no first turn. If you ask what came before our Big Bang, the answer of this physics is the collapse of the black hole interiors of the epoch before ours. If you ask what came before the epoch before ours, the answer has the same form: the collapse of the black hole interiors of an epoch earlier still. I say the same in the books of this physics: the cycle has no first turn. In those books I speak of the epochs one after another, one turn at a time, never of all the epochs gathered into one finished whole.

The accelerating expansion of our epoch does not stop the cycle. The cosmological constant is the energy of empty space that drives the acceleration (Chapter 1). In this physics the cosmological constant belongs to the relation between an observer and that observer's horizon. An observer's horizon is the edge of what the observer can ever see (Chapter 1). At the end of a black hole's interior there is no outside world and no horizon around the end. So the cosmological constant has no effect at the end. The acceleration does not prevent black holes from forming, at every scale. Nor does the acceleration prevent black holes bound to one another from merging. The acceleration also does not prevent the conditions that hold the six small dimensions small from failing at the end of every interior, because those conditions depend on the outside world, and not on the cosmological constant. So the cycle does not need the expansion to stop or to reverse.

## Does Disorder Pile Up?

If the universe goes round and round, does disorder pile up from one round to the next? The physicist Richard Tolman asked that question in the 1930s, and the physicist Roger Penrose has asked the same question of every cycle in which a collapse turns into a new expansion.

Tolman sent the physics journal *Physical Review* a long paper in the autumn of 1931, from the California Institute of Technology in Pasadena. The paper was on what a universe would need in order to expand and contract again and again. The journal received the paper on 18 September 1931. On 13 November the journal received a second paper from Tolman. The second paper was on universes in which processes run one way only, as burning and mixing do. In both papers Tolman worked from Einstein's theory of gravity together with the laws of heat, and he found that a universe could pass through a continued series of expansions and contrac-

tions. In 1934 Tolman gathered the work of both papers into a book, *Relativity, Thermodynamics and Cosmology*, which the Clarendon Press published at Oxford.

Physicists measure disorder by entropy, which Chapter 7 introduced. In Chapter 7 I described entropy as a count of the ways the parts of a thing could be arranged without changing how the thing looks as a whole from outside. In Chapter 8 I added that every count of entropy is made against a context. In this book a context is the respect in which an observer finds something by a comparison. When a thermometer compares this morning's warmth with this evening's warmth, the two times of day are the context. In Tolman's models in which processes run one way only, the entropy made in one cycle is carried into the next cycle. In those models each cycle then swings out to a larger size than the cycle before, and lasts longer. Penrose describes Tolman's models in his book *Cycles of Time*. Penrose writes that the successive cycles "have progressively longer durations and increasingly greater maximum radii". Think of a child on a swing, pushed a little harder at every pass, who goes higher and takes longer on each swing: each swing is like a cycle, and the extra push at each pass is like the entropy carried into the next cycle. If you run the swinging backward in time, the swings grow smaller until the swings reach the first push. So a history whose disorder piles up has only finitely many earlier cycles, and so has a first cycle after all. In 2002 the physicists Paul Steinhardt and Neil Turok put Tolman's worry in one phrase: the "entropy produced during one cycle would add to the entropy produced in the next".

In this physics disorder does not pile up, because no count of entropy crosses the turn. I state the reason in one sentence in my book *The Gravitational Passage*: "Here no count is carried across the turn, for the matter or for the geometry, since each count is relative to the context that ends". The outside world of an epoch is the context of every count made in that epoch. The outside world has no moment at the turn. So each epoch begins its own count, against its own context, with no more entropy than the epoch before. No epoch is larger or lasts longer because the epoch comes later.

A new notebook gives a picture of the fresh count. The pages of a new notebook are numbered from one, because the numbering belongs to the new notebook. Nobody expects page one of a new notebook to carry on from the last page of the notebook before. Each epoch is like a notebook. The counts of entropy made in an epoch are like the page numbers of the notebook. The content crosses the turn, and the form of the content crosses with the content, as Chapter 9 showed. The content is the matter and light of the world. The form of the content is what the matter is and which alternatives the matter has taken. No count crosses the turn, since a count belongs to the context against which the count was made, as page numbers belong to their notebook.

## Penrose's Aeons

In *Cycles of Time* Penrose tells how he came to the idea of his own cycle. Penrose had been thinking about the remote future of a universe whose expansion speeds up. In that remote future the stars are gone. The black holes evaporate, shrinking by their own glow until nothing of them is left (Chapter 5), and the largest black holes evaporate after a googol of years or more, where a googol is a one followed by a hundred zeros. After the black holes have evaporated, nothing is left but light and *gravitational waves*, all spreading and cooling "until eternity". Gravitational waves are the ripples in space that moving masses send out: merging black holes send out such ripples, and since 2015 instruments on Earth have recorded the ripples from merging black holes. Penrose called the remote future of light and ripples the "very boring era". The thought of the very boring era depressed him. On one day in the summer of 2005, Penrose asked who would be there to be bored. We would not be there. Penrose's answer was that the remote future would hold mainly *massless particles*, particles that weigh nothing even when still: the photons that make up light, and the gravitons that make up gravitational waves. And, as Penrose wrote, "it is pretty hard to bore a photon or a graviton".

Penrose's joke has a serious side. A massless particle carries no clock: for a massless particle, in Penrose's words, "the passage of time is as nothing". A clock needs *rest mass*, the mass a body has when the body is still. In a universe where nothing with rest mass is left, no clock can be built, so that universe has no measure of size. Without a measure of size, a huge, cold, thin universe can no longer be told apart from a tiny, hot, dense universe. Penrose put the idea before a conference of accelerator physicists in Edinburgh the next summer, on 29 June 2006. Penrose stated the idea in one line in the written version of the talk: "the remote future of one phase of the universe becomes the Big Bang of the next".

Penrose named his scheme conformal cyclic cosmology. A change of scale can keep the shapes of things, every angle and every path of light, while every size changes. A change of scale of that kind is called *conformal*. A map redrawn at a larger scale is a conformal change of the map, because the redrawn map keeps every angle of every coastline while every distance on the map grows. Penrose calls each whole history of the universe, from its big bang to its remote future, an *aeon*. A conformal change joins the remote future of one aeon, thinned out without limit, to the hot beginning of the next aeon, packed tight. Penrose writes that, as a structure of shapes, "the join is perfectly smooth". For the join to hold, nothing with rest mass may be left at the end of an aeon. So the rest masses of electrons, among other particles, would have to fade: in Penrose's words, "their very rest-masses would very, very gradually fade away, attaining the value zero in the eventual limit".

Penrose answers the question of piled-up disorder in his own way. Penrose holds that black holes destroy the information that falls into them. Once the information is destroyed, the universe has fewer ways to be. The next aeon inherits the smaller range of ways to be, so the entropy of the next aeon begins low.

Of all the cycles in this chapter, Penrose's cycle comes closest to the cycle of this book. In both cycles, the end of one history becomes the beginning of the next history. Both cycles go through a state in which noth-

ing is left to measure against. For Penrose, no rest mass is left to make a clock. In this physics, no matter is left at the end of an interior against which rest, rotation or a large-scale before and after could be fixed (Chapter 6). Both cycles join things that nothing can tell apart. Penrose joins a huge, cold, thin universe to a tiny, hot, dense universe, and in this physics the ends of all the black hole interiors of an epoch are joined as one end. Both cycles begin each new history smooth, with space free of lumps and twists in the shape of space. Penrose proposed the smooth beginning in 1979 as a separate principle. In this physics I derive the smooth beginning as a consequence of the turn, since the new geometry has no past of its own from which to carry lumps. So Penrose arrived at the same structure that this book calls the turn: an end that is a beginning, where nothing is left to measure against, and a joining of things that nothing can tell apart.

The two cycles part in two things: in the place where the new history begins, and in what the new beginning needs. Penrose calls the change from one aeon to the next the crossover, and the crossover lies in the remote future of the whole universe, after every black hole has evaporated, a googol of years or more from now. The crossover needs every rest mass in the universe to fade to nothing. The turn of this book lies at the end of each black hole's interior, and on the clock of a falling body the end of the interior comes, as a limit, after a finite time. The sky empties out of reach beyond our own group of galaxies in a hundred billion to a trillion years (Chapter 1), and the black holes evaporate far later than the sky empties. The turn needs nothing to fade, because the thing that fails at the end of an interior is the context, the outside world in which the six small dimensions were held small.

The two cycles also differ in how the old history and the new history are joined. Penrose matches two geometries across a boundary, with a condition of his own that fixes how the scale of one aeon carries into the next. This physics needs no matching condition, because the ends of the interiors are one when no observer can tell the ends apart by any comparison, and because the new world forms with no earlier identity of its own.

Penrose holds that information is destroyed in black holes. In this physics the form of the content crosses the turn as one averaged form. The averaged form returns in the new sky as the departures from uniformity, the faint differences of density with which an epoch begins (Chapter 9).

## A Bounce at the Smallest Scale

A second kind of cycle comes from attempts by physicists to join gravity with the quantum. In loop quantum gravity, the geometry of space is itself built from separate pieces, so that areas and volumes come in steps. In 2006 the physicists Abhay Ashtekar, Tomasz Pawlowski and Parampreet Singh reported in the journal *Physical Review Letters* that in their model of an expanding universe "the big bang is replaced by a big bounce". A *bounce* is a contraction that turns into an expansion at a smallest size, as a dropped ball turns at the floor. In the model of Ashtekar, Pawlowski and Singh, a universe lies on the far side of the bounce, joined to ours through the bounce.

The bounce of loop quantum gravity shares one important thing with this book. The Planck scale is the scale at which gravity and the quantum meet on equal terms: at the Planck scale the effects of gravity and the effects of the quantum are equally strong. In both the bounce and this book, something definite happens at the Planck scale, and the bending of space stays finite. I record the agreement in my book *The Gravitational Passage*: loop quantum gravity "also reaches a finite curvature at the Planck scale".

Loop quantum gravity and this physics differ over what is built at the Planck scale. The physicists of loop quantum gravity construct a geometry at the Planck scale, and their geometry carries the universe through the bounce. In this physics I construct no geometry at the Planck scale. Physics has two descriptions of the world: Einstein's smooth description of gravity, and the quantum description of the very small. At the Planck scale both descriptions reach the edge of the range in which each description holds, and neither description takes over from the other. The turn is a

limit, and, as I state in my book *At the Edge of Reality*, "Duration, temperature and rate apply to the approach on each side; none of them applies to the turn". The bounce also contracts a whole universe: Penrose, describing the family of bounce models in *Cycles of Time*, writes that the bounce carries a "previously collapsing universe phase" into an expanding one. In this physics the space between the black holes never collapses. The collapse happens only inside the black holes, while the space between the black holes goes on expanding (Chapter 2).

## Colliding Worlds

A third kind of cycle comes from string theory, in which physicists build particles from tiny vibrating strings, and which needs dimensions beyond the four of space and time. In 2001 the physicists Justin Khoury and Burt Ovrut published a paper with Steinhardt and Turok in the journal *Physical Review D*. In the paper the four physicists proposed a universe in which a collision makes the hot Big Bang. The proposed world contains *branes*: surfaces with three dimensions of space, like sheets, set in a space with more dimensions (the word is short for membrane). In the proposal our universe is one brane, at one end of a short fifth dimension, with a second brane at the other end. A third brane peels away from the far end of the fifth dimension and drifts slowly across the gap between the two ends, starting, in the words of the four physicists, "from an otherwise cold, vacuous, static universe". When the third brane strikes our brane, the third brane's energy of motion turns into a hot bath of radiation, and the hot Big Bang begins. Khoury, Ovrut, Steinhardt and Turok called their scheme the ekpyrotic universe. The ekpyrotic universe has one collision only, and so the ekpyrotic universe is not a cycle.

In 2002 Steinhardt and Turok made the ekpyrotic universe into a cycle, in a paper in the journal *Science*. In their model the distance between two branes is described by a field, a quantity with a value at every place, as temperature has a value at every place in a room. In the model of Stein-

hardt and Turok the energy stored in the field is the dark energy that speeds up the expansion today. Steinhardt and Turok write: "The accelerated expansion, caused by dark energy, is an essential feature of our model". The acceleration spreads the entropy, matter and black holes of each cycle out "to negligible levels", and returns the universe to "its original pristine vacuum state". Then the energy of the field falls to zero and below, the expansion stops, and a slow contraction follows. The two branes collide and fly apart, and the one extra dimension between the two branes "momentarily disappears". Steinhardt and Turok also write: "The temperature and density are finite at each transition from crunch to bang". The cycles run without end in both directions: "there is neither a beginning nor an end of time".

In 2019 the physicist Anna Ijjas and Steinhardt proposed a new cycle in the journal *Physics Letters B*. The cycle of Ijjas and Steinhardt has no extra dimensions and no branes at all. In their cycle a field again drives the present acceleration, and the energy of the field again turns negative. The negative energy ends the acceleration and drives a slow contraction. The contraction ends in a smooth bounce in ordinary space and time, far from the Planck scale. In the cycle of Ijjas and Steinhardt the total entropy of the universe grows from cycle to cycle, while space grows faster still. So the entropy within any one observer's view is the same in every cycle. Ijjas and Steinhardt write: "Entropy, black holes, matter and radiation from earlier cycles lie beyond our horizon", spread thinly over the vast space that each new cycle adds.

The colliding worlds share a great deal with this book's cycle. The cycle of Steinhardt and Turok has no first turn, like the cycle of this book. Steinhardt and Turok's cycle also uses the accelerating expansion, as this book's cycle does, to empty the region that each observer can compare with. In their cycles the change between histories has a finite temperature and density, so the change is not a place where physics fails. In this physics, too, Einstein's equations give a point of infinite density, and that point is the edge of one description, not an edge of the world.

In the colliding worlds a field ends each cycle. The energy of the field turns negative, the acceleration ends, and some measure of the whole universe shrinks before the collision or the bounce. The collision or the bounce is then an event inside a description that holds through the collision or the bounce, with a temperature, and in the newest model with a duration. In this physics the dark energy is the cosmological constant, which within our epoch is one number at every time (Chapters 2 and 3). So the acceleration of our epoch never ends, and no measure of the space between the black holes ever shrinks. The cycle of this book does not need the acceleration to end, because the turn comes at the ends of the black hole interiors, and the acceleration does not prevent the interiors from ending. And the turn is a limit, with no temperature and no duration.

The colliding worlds and this physics also treat entropy differently. In the model of 2002 the acceleration dilutes the entropy of each cycle. In the model of 2019 the total entropy grows from cycle to cycle. If a total of entropy were carried from cycle to cycle, the total would be a count made across epochs. In this physics no comparison is made across the turn, so there is no context against which a total across epochs could be counted, and so each epoch begins its own count.

The extra dimensions of the brane models differ from the six small dimensions of this physics. In the brane models an extra dimension is a region of space in which branes sit and move, and the width of the extra dimension is a field whose changes bring the collision. In this physics the six small dimensions are dimensions of possibility, and an observer encounters the six small dimensions only as the range of possibilities from which each finding is one selection. Nothing travels through the six small dimensions. I give the plain picture in my book *Measurement*: "You cannot walk to the outcome that did not happen". So in this physics no brane has anywhere to drift. In the brane models the extra dimension shrinks to nothing for a moment at the collision. The six small dimensions of this physics do the opposite: the six small dimensions grow as the end of an interior comes near, and in the new epoch the six shrink back to their held small size.

The last difference is in what goes on from cycle to cycle. In the cyclic models a field and a space continue through the collision or the bounce. In the cyclic models the galaxies of the next cycle grow from a faint unevenness. The quantum trembling of the field makes the faint unevenness during the contraction. In the newest model the black holes of earlier cycles still exist, far beyond our horizon, in the same space as ours. In this physics only the form of the content crosses the turn, of all the things that a comparison could register as the same thing on both sides of the turn. No old black hole lies beyond our horizon as an object. The faint unevenness of our sky is the form of the content of the epoch before, averaged into one pattern (Chapter 9).

## Where One History Gives Way to the Next

Look up from the back step once more. Our epoch gives way to the next epoch at the ends of the black hole interiors, and no comparison of yours is made at that end, so the change lies nowhere in the sky that you can compare with, near or far, now or in the sky's remote future. The other physicists put the change elsewhere. Tolman's closed universe falls back on itself again and again and carries its disorder forward from cycle to cycle. Penrose's aeons cross over at the remote future of the whole universe. The bounce of loop quantum gravity carries a collapsing universe through the Planck scale. The brane models go through a collision or a bounce at the end of a contraction driven by a field.

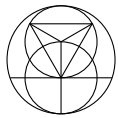
The cycle of this book turns at the ends of the black hole interiors of an epoch, which are one end. Chapters 1, 6 and 8 have already given the turn's three grounds. The first ground is that content cannot be without a context, which is the third axiom of Chapter 8. The second ground is that a difference no comparison can register is no difference (Chapter 6). The third ground is that the outside world of every observer empties (Chapter 1). The turn follows from the three grounds, and so does the cycle, with no first turn.

## What This Means for You

The sky over your step is not the first sky. The microwave background is warmer in some places and cooler in others by about one part in a hundred thousand of its temperature. The faint pattern is the form of the content of the epoch before ours, averaged into one pattern across the whole sky. Nothing of the epoch before ours remains to be found as a thing: no old star, no old black hole, no record and no count. The black holes of our own epoch include the black hole at the center of the Milky Way, and whatever falls into any of those black holes comes to the end that the interiors of all black holes share, from which the next epoch begins.

> **Key idea.** Our epoch is one turn of a cycle with no first turn. Black holes form in each epoch, their interiors share one end, and the next epoch begins from that end. No count of entropy crosses the turn, so disorder does not pile up, and no epoch is larger or lasts longer because the epoch comes later. Three other cycles each describe how one history gives way to the next: Penrose's aeons, the bounce of loop quantum gravity and the colliding branes. The cycle of this book differs from all of those cycles in the place where one history gives way to the next, which in this book is the ends of the black hole interiors. The cycle of this book also differs in what the change needs, which is three grounds: content has a context, a difference no comparison can register is no difference, and every observer's outside world empties. The cycle of this book matters because the far future of our sky then lies inside a cycle that has run before and runs again.

What comes after the dark?



Chapter 12

# What Comes After the Dark?

## The Answer in One Walk

What comes after the dark? A new sky comes after the dark of the emptied sky, and the same law of the world holds again under the new sky. The law is the structure of the world that this physics derives. The new sky begins from the turn, the one end that the interiors of all black holes share. In this physics the far future of the universe is a long emptying of every sky. The long emptying ends in a turn, and not in a final dark. At the turn a new epoch begins: a new era of the world, which makes stars, galaxies and black holes of its own.

Go out to the back step one last time, and take the whole walk, from the sky you can see to the turn and beyond. I argued each step of the walk below, with its reasons, in an earlier chapter, and in this chapter I set the steps out in one line, so that you can see the whole walk at once.

## The Sky Thins

Count the faint smudges in the sky once more. Each smudge is a galaxy, an island of stars, and the expansion of the universe carries each galaxy away from us (Chapter 1). The expansion of the universe is the growth of the distances between galaxies that are not held together by

gravity. Astronomers have measured that the expansion is speeding up. In an expansion that speeds up, every observer has a horizon: a boundary beyond which no event can ever send a signal to that observer. One by one the galaxies cross your horizon, and the light of each galaxy reaches you only stretched and dimmed, and then the light of that galaxy does not reach you at all.

Chapter 1 describes how, in 2007, the physicists Lawrence Krauss and Robert Scherrer worked out what astronomers in our own neighborhood of the universe would see in the far future, after the distant galaxies have crossed the horizon. The astronomers of the far future would see one galaxy: the single galaxy that the Milky Way and Andromeda will by then have become. The expansion would have carried every more distant galaxy beyond the horizon, so the sky of the far-future astronomers would look still, and nothing in their sky would show that the universe expands.

Meanwhile gravity draws together the matter that stays near, and the expansion carries the rest of the matter away. Our own group of galaxies is our own galaxy, the Milky Way, together with Andromeda and some dozens of smaller galaxies, all held together by gravity. Astronomers' standard calculation shows that the sky beyond our own group of galaxies empties out of reach in a hundred billion to a trillion years. Over far longer times still, every structure that remains ends inside a black hole or is carried away alone. A body carried away alone is carried by the expansion beyond the reach of all other matter. Black holes give off a faint glow, and by that glow each black hole slowly evaporates, over a span of time longer even than the time the remaining structures take to end. Don Page calculated how fast a black hole loses its mass to the faint glow: a black hole of the Sun's mass takes about two times ten to the sixty-six years to evaporate. So the sky empties first, long before the black holes evaporate. In Chapter 1 I summed up the emptying of the sky in one plain sentence: the populated sky is a passing stage of our epoch.

## What the Dark Is Not

Three of the endings that popular accounts describe do not come at all: the Big Crunch, in which the galaxies fall back together; the Big Rip, in which the expansion tears everything apart; and a change of empty space into something else.

The galaxies do not fall back together (Chapter 2). In the history of the universe that astronomers piece together from present measurements, space in our epoch is flat: lines that start out side by side stay side by side for ever. The cosmological constant is the energy of empty space itself, and the cosmological constant drives the speeding up of the expansion. The cosmological constant is positive, and within our epoch the cosmological constant is one number at every time, so the cosmological constant has no way to change its size or its sign. In every epoch the same law sets the cosmological constant. Because space is flat and the cosmological constant is positive, the expansion never slows to a stop, whatever the density of matter (the amount of matter in each cubic meter of space). This physics counts six small dimensions beside the three dimensions of space and the one of time: six further directions that every point of space carries, curled up far smaller than the core of an atom. The six small dimensions have no second state to fall into. The collapse that ends an epoch happens inside black holes, while the space between the black holes keeps expanding. Our epoch does not fall back.

The expansion does not tear things apart (Chapter 3). Dark energy is whatever drives the speeding up of the expansion. The expansion could tear things apart only if the push of the dark energy grew. In this physics the dark energy is the cosmological constant. Physicists call the ratio of a substance's pressure to its density the equation of state of the substance, and for the cosmological constant the equation of state is exactly minus one, so the push of the cosmological constant never grows. A push that stays the same is already part of the balance that holds a galaxy, a planet

and an atom together today, so a push that stays the same never unbinds a galaxy, a planet or an atom. A bound thing is a thing held together by its own gravity, or, for an atom, by the forces among its particles. A bound thing ends in one of two ways: by its own gravity, inside a black hole, or carried away alone. The expansion never tears apart anything that is bound.

Empty space does not change its nature (Chapter 4). Physicists call the settled state of empty space, with nothing added, a vacuum. A vacuum could decay only into a second, lower vacuum. The six small dimensions have one held shape, and no second shape to tunnel to (to tunnel is to pass, as quantum physics allows, from a held state into a lower one without climbing over the barrier between the two). The large world around the six small dimensions holds the six small dimensions in their one shape. The hold on the six small dimensions ends in two places: at the end of a black hole's interior, and, for a body carried away alone, when nothing is left within the body's reach to compare against. Neither end of the hold is a decay. The vacuum of our epoch is the only vacuum of its kind, and the vacuum of our epoch ends where every epoch ends.

## Matter and the Watcher

The stars over the back step go out one by one (Chapter 5). The stars leave cold ashes of two kinds, white dwarfs and neutron stars, and both kinds are held up against their own gravity without heat. A white dwarf is held up because no two of its electrons can crowd into the same state. A neutron star is held up because no two of its neutrons can crowd into the same state. The push of the force between the neutrons also holds a neutron star up. The ashes cool and keep their matter, because the proton does not decay. The proton is the particle with a positive electric charge in the nucleus of every atom. Each ash ends inside a black hole, or is carried away alone, carried by the expansion beyond the reach of all other matter. The black holes themselves evaporate last of all. Matter does not wear

away. The forms of matter are the atoms, stars and bodies that matter makes in our epoch. The forms of matter last until the hold on the six small dimensions ends, inside a black hole or for a body carried away alone.

What happens to the watcher who is still on the step (Chapter 6)? In this physics an observer is anything that compares one thing with another: you on the step, an astronomer at a telescope, a camera. Every observer ends inside a black hole or carried away alone. When the sky has emptied, nothing is left against which to measure "not rotating", or "before and after" between distant things, because each was always a comparison with the distant matter. The one-way order inside each comparison stays: the order in which you find something and then know it. Time does not stop. The turn is not an event in time, because no comparison can be made across the turn, a before compared with an after. The end of the sky is the end of what an observer can compare with, and not the end of time.

Can a watcher keep thinking about the sky for ever (Chapter 7)? In 1979 the physicist Freeman Dyson planned a way: think more slowly and more coldly, and sleep for long stretches between thoughts. In 2000 the physicists Lawrence Krauss and Glenn Starkman answered that three things prevent Dyson's plan from working: a horizon, a finite store of matter and energy, and a floor of temperature. In this physics a thought is an actual comparison with something else, kept in a record, with time running one way. When the sky has emptied, every thinker is at the end of a black hole's interior or alone. No thought passes from either place to the next epoch. Thinking itself begins again in the next epoch, where comparison begins again. So no one thinker thinks for ever, but thinking does not end.

## The Turn

The history of the universe goes on past the dark sky (Chapter 8). The old fear of a heat death is the fear of a final state in which everything has one temperature and nothing ever happens again. This physics has three independent grounds for holding that the emptying never comes to rest in a heat death. Each ground is enough by itself.

The first ground is the third axiom of this physics: content cannot be without a context. The content of a comparison is what an observer finds by making the comparison. The context is the respect in which the observer finds the content. When you read a thermometer in the morning and in the evening, the temperature is the content and the times of day are the context. A context must be restored, because the content of an epoch does not cease when the outside world of the epoch empties.

The second ground is the Incommensuration Theorem, a structural fact about the nature of knowing. The Incommensuration Theorem says that, at the foundation of any comparison, symmetry and continuity cannot both be perfect together. When a thing stays the same through a change, we call the thing symmetric. A law that holds in every city is symmetric, because the law stays the same from one city to the next. When a thing has no break, we call the thing continuous: a ramp is continuous, because a ramp rises with no sudden step anywhere. A featureless emptiness would be the same everywhere and would have no break anywhere, so a featureless emptiness would be perfectly symmetric and perfectly continuous at once, at the bottom of what is found. So no observer ever finds a featureless emptiness.

The third ground is what entropy is. Entropy is a count of the arrangements of a thing's parts that leave the thing looking the same from outside. Every count of entropy is made against a context. So when the context has emptied, the count of entropy has nothing to be counted against.

On all three grounds the emptying cannot come to rest as a final dark. The ends of all black hole interiors are one end, because no observer can tell the end of one interior from the end of another. The next epoch begins from the one end of all the black hole interiors. At the one end of the interiors, the six small dimensions are no longer held small, and the geometry of all ten dimensions (the three of space, the one of time and the six small ones) restores a large world with three large directions of space. The emptying ends in a turn, and not in a final dark.

## What Crosses

What crosses the turn (Chapter 9)? Two different things go by the name of information. The first thing called information is the form of the content: what the matter is, and which alternatives the matter has taken. The second thing called information is a count of states, made against a context. The form of the content crosses the turn, as one averaged form with no mark of which black hole it came through. No count crosses the turn, and no length, no record and no entropy. The forms of matter do not cross either, because the forms of matter end where the hold on the six small dimensions ends. The law is not carried across the turn, but the law returns: the same law holds again on the far side of the turn, with the same ten dimensions and the same shape of the six small ones.

We have already seen what the form of the content looks like in our own sky. Chapter 9 describes the measurement that shows the form of the content. George Smoot of the Lawrence Berkeley Laboratory first announced the measurement on 23 April 1992, at a meeting of the American Physical Society in Washington. At the meeting Smoot reported what the Cosmic Background Explorer, a satellite known as COBE, had found in its first year of mapping the microwave background, the faint afterglow of the Big Bang that reaches us from every direction. The glow is not perfectly even. The glow is warmer here and cooler there, by about one part in a hundred thousand of its temperature. The warmer and cooler patches

of sky are far larger than any galaxy. The paper of the COBE team followed in September 1992, in *The Astrophysical Journal Letters*. The faint differences of warmth across the sky are the seeds from which, by gravity, our galaxies grew. I identify the faint differences with the form of the content of the epoch before ours, averaged into one pattern across the whole sky. The pattern is one pattern because the end the pattern comes from is one end. The pattern is not a patchwork of separate pieces, one for each black hole. What crosses is the form of the content, the law returns, and nothing crosses as itself: nothing arrives on the far side of the turn as a thing that a comparison could register as the same thing on both sides.

So no one crosses on purpose (Chapter 10). Nothing crosses the turn as itself: not a body, not a readable record, not a person, not a message. No path and no act joins the next epoch to ours, because whatever a path can reach belongs to our own one world. Nothing escapes as itself. There is no other universe to escape to.

## Again, With No First Turn

Have the emptying of a sky and the turn after it happened before (Chapter 11)? Our epoch began from the end of the epoch before it, and that earlier epoch began from the end of another. The cycle of epochs has no first turn. No count of entropy crosses a turn, so disorder does not pile up, and no epoch is larger or longer for coming later. Other physicists have proposed other cycles: Richard Tolman's growing cycles, each larger and longer than the last; Roger Penrose's aeons, each a whole history of the universe; the bounce of loop quantum gravity, in which a collapsing universe turns into an expanding one; and the colliding branes, sheets with three dimensions of space set in a space with more dimensions. The cycle of this book differs from each of the other proposed cycles in where one history gives way to the next: in the cycle of this book, one history gives way to the next at the ends of the black hole interiors. The cycle of

this book rests on three grounds: content has a context, a difference no comparison can register is no difference, and every observer's outside world empties. Our epoch is one turn of a cycle with no first turn.

When the steps of the walk are put together, the far future of the universe runs as follows. The sky beyond our own group of galaxies empties out of reach in a hundred billion to a trillion years. Over longer times still, the matter that stays ends inside black holes or is carried away alone. Nothing falls back, nothing is torn, and empty space keeps its nature. The forms of matter last, and every watcher keeps comparing, until the path of each body ends inside a black hole or alone. At the end that the interiors of all black holes share, the turn comes. A new epoch begins under the same law as our epoch. The new epoch carries the form of the content of the old epoch as one averaged form. The new epoch makes stars and black holes of its own, and in time the sky of the new epoch empties too.

## What This Means for You

Tonight the sky over your step is generous, full of stars and galaxies, and the full sky is passing. The expansion will carry the galaxies you count out of sight, and the stars near you will go out. The black holes of our epoch will take in the matter that stays, the black hole at the center of the Milky Way among them. Yet the emptying of your sky is not a final dark. The faint pattern in the microwave background shows you already what comes after the dark of an epoch: a new sky, carrying the form of the content of the sky before. Nothing of you crosses the turn as yourself, and no message of yours crosses as a message, but the form of the content of everything that falls into the black holes crosses. On the far side of the turn, the law under which you look up tonight holds again.

**Key idea.** After the dark comes a new sky. The sky beyond our own group of galaxies empties out of reach in a hundred billion to a trillion years, and then the matter that stays ends inside black holes or is carried away alone. Nothing falls back, nothing bound is torn apart, and empty space keeps its nature. Matter keeps its forms, its atoms, stars and bodies, until the hold on the six small dimensions ends, inside a black hole or for a body carried away alone, and the forms of matter do not cross the turn. The emptying ends in a turn, at the end that the interiors of all black holes share. At the turn the form of the content crosses as one averaged form, but nothing crosses as itself. The form of the content is what the matter is, and which alternatives the matter has taken. The law of our epoch holds again in the new epoch, and the new epoch makes its own stars and black holes and in time empties too, in a cycle with no first turn. The answer matters because people have long feared a final dark, and the answer shows that the long emptying is one stage of the world, and not the end of the world.

Picture, then, the last thing this book can show you: the young sky of the next epoch, a sky that no clock of ours counts toward and that no comparison of ours will ever reach. The young sky is filling with galaxies. The young sky carries a first faint pattern, warmer here and cooler there, and the pattern is the form of the content that our black holes took in, averaged into one. Under the young sky, the conditions are present again under which watchers arose in our epoch. Picture a step on a world of the next epoch, and someone standing on the step on a clear night, counting the faint smudges overhead. Nothing of us is in the picture as itself: not our names, not our records, not our sky. What is in the picture is a new sky over a new step, and the same law.

# For the Specialist

## How This Appendix Is Laid Out

This appendix sets out, chapter by chapter, what each chapter's answer rests on, for a physicist or a philosopher who wants the reasoning in full. For each chapter it gives the answer in one sentence; the grounds, each named, with the book, chapter and section of the collection where the ground is argued; the standing of each step; and the reported and measured values the chapter uses, each with its primary paper. The full references are in the References. The measurements still to come are in Appendix B.

Every step carries one of seven standings, and each standing has one meaning here.

| Standing | What it means in this appendix |
|---|---|
| derived | The step follows, by steps the collection gives, from the axioms, from the Incommensuration Theorem, from a theorem of mathematics, or from a structure the collection derives. |
| derived given a stated premise or identification | The step follows by steps the collection gives once a premise or an identification, named with the step, is granted. |
| identification | A step, made in the first person, from the structure of comparison to something in the world. |
| structural value | A number fixed by the derived structure: a count, a ratio or an exponent. |
| measured input | A value taken from measurement and used in a step. |

| | |
|---|---|
| reported | Established physics that the collection reports and does not derive again. |
| not argued | A step the collection does not take; it is stated here as the edge of the answer's scope. |

Two grounds recur in every chapter, and they are stated once here. The third axiom holds content and context distinct, inseparable and non-interchangeable, so that no content stands without a context in which it is content. The Incommensuration Theorem is a structural fact about the nature of knowing: symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison, and neither can asymmetry and discontinuity (*The Gravitational Passage*, Chapter 3, Section IV).

Three settled usages hold throughout this appendix. The Planck scale is the scale of length, time and energy at which gravity and the quantum meet on equal terms; there the smooth description of space and time and the stepwise description of the quantum both reach their edge, and neither takes over from the other (*The Gravitational Passage*, Chapter 17, calls this the modal boundary). The strength of gravity is taken from measurement, and the size of the six small dimensions is fixed in the unit of length that this strength sets, the Planck length (*The Gravitational Passage*, Chapter 18, Questions). "The forms of matter" are the definite forms matter takes in this epoch (atoms, stars, bodies), which end where the hold on the six ends; "the form of the content" is what the matter is and which alternatives it has taken, information in the first sense, which crosses the turn as one averaged form.

Where a ground is argued in one book and told again in others, it is counted once, and the table names the book where it is argued, with the retellings after it. Where a passage is quoted, it is quoted from the book named, word for word.

## Chapter 1. What Happens to the Sky We Can See?

The answer: for every observer, the part of the universe that the observer can ever compare with empties within about a hundred billion to a trillion years, as matter clumps into black holes or is carried beyond the cosmological event horizon, and black holes evaporate only on a far longer timescale, so the populated sky is a passing stage of our epoch.

| Ground | Where it is argued | Standing |
|---|---|---|
| The accelerating expansion gives every observer a cosmological event horizon, a boundary beyond which no event can ever send that observer a signal. | *The Gravitational Passage*, Chapter 18, Section III; told again in *At the Edge of Reality*, Chapter 12, "The Bound of What Can Ever Be Compared". | reported |
| Content beyond an observer's event horizon is no part of that observer's exterior, because it cannot be compared with that observer in principle. | *The Gravitational Passage*, Chapter 18, Section III. | derived (from the definition of an observer's exterior as what that observer can ever compare with) |
| Within the horizon matter clumps: stars form, burn out and leave remnants; remnants accrete and merge; bound structures end in black holes; what they do not take in departs, as ejected bodies or as radiation. | *The Gravitational Passage*, Chapter 18, Section III; told again in *At the Edge of Reality*, Chapter 12, "Clumping and Departing", and *The View from Inside*, Chapter 16, "Nowhere Else to Be". | reported |

| | | |
|---|---|---|
| Black holes glow and evaporate, on a timescale far longer than the emptying, so the emptying comes first. | *The Gravitational Passage*, Chapter 18, Section X; told again in *At the Edge of Reality*, Chapter 12, "The Faint Glow of a Black Hole" and "Two Timescales". | reported |
| Every path through the space between black holes has two exits: into a hole, or alone while everything else passes beyond its horizon. | *The Gravitational Passage*, Chapter 18, Sections III and IV; *The View from Inside*, Chapter 16, "Nowhere Else to Be"; *What the Beginning Left Behind*, Chapter 1, "How an Epoch Ends, in Eight Steps", the third step. | derived (from the reported dynamics of the third row) |
| Observers of the far future lose the evidence of the expansion, because the distant galaxies pass beyond the horizon. | *The View from Inside*, Chapter 2, "What the Cosmological Constant Tells Us". | reported |

The steps run in the order of the table. The horizon is reported physics of an accelerating expansion. The step from the horizon to the emptying of the exterior uses the collection's definition of the exterior, and *The Gravitational Passage* states the result: "Over sufficiently long times, every observer's comparable exterior therefore empties". The two durations are reported, and *What the Beginning Left Behind* names their source: "Both spans come from the known physics of stars, of black holes and of the expansion". The two exits follow from the clumping and the departing, and they are the starting point of Chapters 6 and 8.

The scope of the answer: it covers the emptying of every observer's comparable exterior within our epoch. What becomes of an observer at the end of either exit is the subject of Chapter 6, and what follows the emptying is the subject of Chapter 8.

| Reported or measured value | Primary source |
|---|---|
| The flat base model gives a matter share $\Omega_m = 0.315 \pm 0.007$ (read: the share of matter in the energy of a flat universe is 0.315, give or take 0.007) and a present expansion rate $H_0 = 67.4 \pm 0.5$ kilometers per second per megaparsec, so the share of the cosmological constant is about 0.685 and its sign is positive. | Planck Collaboration, Aghanim and others (2020) |
| All structures beyond an observer's own bound cluster of galaxies are driven outside the de Sitter event horizon on a timescale of the order of 100 billion years, and observers in that island lose the evidence of the expansion. | Krauss and Scherrer (2007) |
| In a universe dominated by a cosmological constant, "presently observable distant sources will disappear on a time-scale comparable to the period of stellar burning". | Krauss and Starkman (2000) |
| Normal star formation in galaxies ends by the cosmological decade $\eta \approx 14$ ($\eta$ is the base-ten logarithm of the time in years); the disruption of the galaxy unfolds over $15 < \eta < 25$; evaporation of black holes by Hawking radiation over $60 < \eta < 100$. | Adams and Laughlin (1997) |
| Black holes emit thermally, and the emission slowly lowers their mass. | Hawking (1975) |
| The lifetime of a hole of mass M much greater than $10^{17}$ grams is $2.16 \times 10^{66}\ (M/M_\odot)^3$ years (read: two point one six times ten to the sixty-six years, times the cube of the hole's mass in units of the Sun's mass); for one solar mass that is about $10^{66.3}$ years. | Page (1976) |

## Chapter 2. Will It All Fall Back?

The answer: in the history that the present measurement reconstructs, the homogeneous model of our epoch is spatially flat and its cosmological constant is positive and one number at every epoch, so its expansion rate

never reaches zero whatever the density of matter; the collection gives the constant no way to change size or sign and the internal space no second vacuum to tunnel to; and the collapse that ends an epoch happens inside black holes while the space between keeps expanding, so our epoch does not fall back.

The question has three forms: a recollapse because the matter density is high enough (Form A); a recollapse because the constant later shrinks, changes sign, or tunnels to a negative value (Form B); and whether the collapse that ends an epoch in this account is a recollapse of the whole (Form C). A recollapse here means that the expansion rate H of the homogeneous model falls to zero and then becomes negative.

| Ground | Where it is argued | Standing |
|---|---|---|
| The Friedmann equation of a homogeneous universe. | *The Gravitational Passage*, Chapter 16, Section IV, and Chapter 13, Section VI. | reported |
| The homogeneous model of each epoch is spatially flat: the curvature is a constant of integration set at the turn, where no length and no count of the old epoch passes. | *The Gravitational Passage*, Chapter 18, Section IX; told again in *Side by Side*, Volume Two, Appendix O, "Why the New Epoch Is Flat", and *At the Edge of Reality*, Chapter 19, "Why Space Is Flat". | derived given a stated premise (the new geometry has no prior identity) and an identification (every epoch that leads to a turn makes structure) |
| The cosmological constant is positive: every factor of the formula for its energy density is positive. | *The Gravitational Passage*, Chapter 12, Section IV, with Chapter 13, Section II, and Chapter 11, Section III. | derived given the identification of the constant with the accessible share of the vacuum's energy |

| | | |
|---|---|---|
| Within one geometry the constant does not vary, by the contracted Bianchi identity with the conservation of the content's stress-energy. | *The Gravitational Passage*, Chapter 13, Section VI; told again in *The Concept Branches*, G-IV, and *The View from Inside*, Chapter 15, "One Map, One Scale". | derived (a theorem of the geometry) |
| The one value is fixed by the present measurement, and the history reconstructed from that measurement carries it at every epoch, before the present and after it. | *The Gravitational Passage*, Chapter 13, Section VI; told again in *The View from Inside*, Chapter 15, "Which Measurement Fixes It". | derived (from the first axiom and the definition of the real) |
| The internal space has one held configuration: two moduli, both fixed at one point, and no flux. | *The Compactification*, Chapter 2, "One Vacuum", Sections III to VII and IX. | identification (homogeneity of each factor) joined to a theorem (Schur's lemma); derived (the floor, from the third axiom) |
| Every observer's comparable exterior empties under a continuing, accelerating expansion. | *The Gravitational Passage*, Chapter 18, Section III. | reported |
| The end of a black hole's interior lies at no moment of the exterior's time. | *The Gravitational Passage*, Chapter 18, Section I. | reported (results of general relativity), with the placement derived |
| The ends of all interiors are one, by the principle that a difference no comparison can register is no difference, while the interiors themselves are not one. | *The Gravitational Passage*, Chapter 18, Section II; told again in *At the Edge of Reality*, Chapter 11. | derived given the principle of comparison and the stated premise that the new context registers no distinction of the old exterior |

| | | |
|---|---|---|
| A body carried away alone reaches the condition of the turn without falling anywhere. | *The Gravitational Passage*, Chapter 18, Questions, with Sections IV and VI. | derived given the third axiom and inertia as a comparison |
| The emptying cannot come to rest, by the Incommensuration Theorem, and context is restored. | *The View from Inside*, Chapter 16, "Context Must Be Restored". | derived |
| Inside an interior, on the upper end of the Kasner arc, the three large directions shrink while the six grow, the time reverse of the origin of an epoch. | *The Gravitational Passage*, Chapter 19, Section II, and Appendix B. | derived (the Kasner rules) with an identification (the placement at the end point of the arc) |

Form A. The Friedmann equation is $H^2 = (8\pi G/3)\rho - kc^2/a^2 + \Lambda c^2/3$ (read: the square of the expansion rate equals eight pi times Newton's constant, over three, times the energy density, less the curvature term, plus the cosmological constant times the square of the speed of light, over three). A recollapse needs H to pass through zero (reported). The curvature term is zero (derived given the premise and identification of the flatness ground), and on this account the total of matter does not set the curvature, so a higher density only enlarges a positive term (derived given the same premises). With the curvature term zero, the density term not negative and $\Lambda$ positive, $H^2$ is at least $\Lambda c^2/3$ at every epoch, so H never reaches zero, for every density (derived).

Form B. The constant is one number within one geometry (derived), it enters the field equations as their constant term because a vacuum energy the same for every comparer in uniform motion has a stress-energy proportional to the metric (derived given the identification of the accessible share), and it is fixed once by the present measurement (derived). *The Gravitational Passage* states the theorem without qualification: "So within one geometry $\Lambda$ does not vary. This is a theorem of the geometry, and it

uses no measurement and no value of w". So the equation of state is exactly minus one and no field's energy can drift or turn negative (derived). The internal space has no second held configuration, so there is no lower vacuum to tunnel to while the exterior stands (identification joined to a theorem; derived for the floor). The energy density formula is $\rho_\Lambda = c_1 \, f \, M_{Pl}^{\,4} \, / \, S$ (read: the energy density of the constant equals the first Chern coefficient $c_1$, times the trim f, times the fourth power of the Planck mass, divided by the entropy S of the observer's particle horizon). Here $c_1 = 3$ (structural value: the coefficient of the first Chern class of the complex projective plane), $f = 1 - 3/(8\pi)$ (structural value: one less three over eight pi, positive because eight pi exceeds three), and S is a count and so positive; every value the formula gives is therefore positive (derived). The standing of the positive sign includes the two coefficients of order one at the values *The Gravitational Passage* states, in Chapter 13, Questions. At the end of an interior the constant acts as nothing at all, because the exterior on which its definition rests has dissolved, so the turn needs no change in the constant (derived given the identification of the accessible share).

Form C. The collapse that occurs is the collapse of bound structures into black holes (reported). The ends of the interiors lie at no moment of the exterior (derived from the reported results of general relativity), so the exterior's history holds no moment at which everything collapses. The ends are joined by indiscernibility of their limits and not by the contraction of the space between the holes (derived given the principle of comparison). A body carried away alone reaches the failure of the compactification conditions while it moves apart from everything else (derived given the third axiom). So the end of an epoch is reached path by path, each on its own clock, and the exterior is never contracted as a whole (derived).

The scope of the answer: it covers the homogeneous expansion of our epoch from the present measurement into the far future, the constant of that history, and the way the epoch ends. The stability of the vacuum of the Higgs field is the subject of Chapter 4. Whether the content of a body

carried away alone re-emerges in the one new epoch that the interiors share is not argued in *The Gravitational Passage* (Chapter 18, Questions); *The View from Inside* states that both exits lead to the turn (Chapter 16, "Context Must Be Restored").

| Measured value beside these steps | Primary source |
|---|---|
| The curvature share $\Omega_K = 0.001 \pm 0.002$ (Planck with baryon acoustic oscillations): flat within the measurement. | Planck Collaboration, Aghanim and others (2020) |
| The share of the cosmological constant is about 0.685 in the flat model, so the constant is positive; with $H_0 = 67.4$ the constant is $\Lambda = 3\Omega_\Lambda H_0^2/c^2 \approx 1.09 \times 10^{-52}$ per square meter (computed from the published values). | Planck Collaboration, Aghanim and others (2020) |
| For these values the expansion rate of the constant alone, $H_0\sqrt{\Omega_\Lambda}$, is about 55.8 kilometers per second per megaparsec (computed), below the measured present rate of 67.4. | Planck Collaboration, Aghanim and others (2020) |
| Of the stars of a galaxy, about 1 to 10 percent fall to the central black hole and the remainder are evaporated from the galaxy. | Adams and Laughlin (1997) |

The measured equation of state of the dark energy is set out in Appendix B.

## Chapter 3. Will the Expansion Tear Us Apart?

The answer: in this physics the energy of empty space is the cosmological constant, one number in the one geometry of our epoch, so its equation of state is exactly minus one and the condition for a rip, an equation of state below minus one, is not met; a constant term adds to every bound structure an outward term that is the same at every time and is already part of what holds the structure now, so the expansion tears apart no galaxy, planet or atom, and bound structures end by their own gravity inside black holes.

The rival account, in its own terms: Caldwell, Kamionkowski and Weinberg (2003) call a dark energy whose equation of state lies below minus one "phantom energy"; its density grows as the universe expands and becomes infinite in a finite time, and before that time the outward repulsion inside every bound system exceeds what binds it, so clusters, the Milky Way, the solar system, the Earth, molecules, atoms and nuclei come apart in that order. For an equation of state of exactly minus one, the same paper finds no rip and states that a system bound now stays bound. The equation of state w is the ratio of a component's pressure to its energy density; $w = -1$ (read: w equals minus one) is the value of a density that does not change as the universe expands.

| Ground | Where it is argued | Standing |
|---|---|---|
| The constant is the accessible share of the vacuum's energy, and it enters the field equations as their constant term. | *The Gravitational Passage*, Chapter 13, Sections II and VI. | identification; the entry as the constant term is derived given it |
| Within one geometry the constant does not vary (the contracted Bianchi identity). | *The Gravitational Passage*, Chapter 13, Section VI; told again in *The Concept Branches*, G-IV, and *The View from Inside*, Chapter 15. | derived |
| The value is fixed once by the present measurement and carried at every later epoch. | *The Gravitational Passage*, Chapter 13, Section VI. | derived (the first axiom and the definition of the real) |
| The equation of state of the constant is exactly minus one. | *The Gravitational Passage*, Chapter 13, Section V. | derived given the identification of the first row |

| | | |
|---|---|---|
| The list of kinds holds one scalar field, the Higgs field, and no further field kind. | *The Story of the Particles*, Level 9, Section IV; told again in *The Concept Sequence*, Chapter 41, and *The Kinds of Particle*, Chapter 6, Section IV. | derived (the structure of the kinds) |
| The energy of the Higgs field is constant after the electroweak crossover. | *The Gravitational Companion*, "Comparisons at Single Steps", Section VII, citing *The Coming of the Kinds*, Chapter 4, Section IV. | reported |
| The internal space leaves one vacuum, the same at every point and in every epoch. | *What the Beginning Left Behind*, Chapter 21, "What the Six Left Fixed", from *The Compactification*, Chapter 2. | derived given the identifications on which the hold rests |
| A density that followed the particle horizon would have an equation of state above minus one third, so it would never drive acceleration and would not reach the rip condition. | *The Gravitational Companion*, "Comparisons at Single Steps", Section VII; *The View from Inside*, Appendix A, Section V. | reported (Li 2004, as the books report it) |
| Around a spherical mass with a constant $\Lambda$ the geometry is the Kottler solution, whose departure from the Schwarzschild geometry is negligible at the scale of the solar system. | *The Gravitational Passage*, Chapter 16, Section III. | reported (Birkhoff's theorem and the Kottler solution) |
| What is bound stays with the observer's structure and ends inside black holes; what is not bound is carried away. | *The Gravitational Passage*, Chapter 18, Section III; told again in *At the Edge of Reality*, Chapter 12, "Clumping and Departing". | reported |

| | | |
|---|---|---|
| Gravitation distorts space where content is; the cosmological constant distorts the course of the whole, the same at every place and time. | *The Weight of Possibility*, Chapter 2, Section II. | identification |
| The faster expansion does not stop bound holes from merging. | *What the Beginning Left Behind*, Chapter 21, "What the Six Left Fixed", from *The Gravitational Passage*, Chapter 18, Section XII. | derived given the identification of the accessible share |
| What ends the forms of matter is the failure of the conditions that hold the six, at the end of an interior or for a body left alone, and not a pull of the expansion. | *The Gravitational Passage*, Chapter 18, Questions, with Section VI; told again in *At the Edge of Reality*, Chapter 13, "A Body Carried Away Alone". | derived given the compactification conditions |

Part one, the rip condition. *The Gravitational Passage* states the equation of state directly: "The information deficit formula predicts the equation of state of the cosmological constant to be $w = -1$ exactly". The rip condition is reported (Caldwell, Kamionkowski and Weinberg 2003). An equation of state of exactly minus one is not below minus one, so the collection's dark energy does not meet the condition (derived given the identification). No field of the content supplies a growing density beside the constant: the content holds the listed kinds and no others (derived), and its one scalar field has a constant energy after the crossover (reported). With $\Lambda$ constant and positive, the expansion rate stays above the de Sitter rate $\sqrt{(\Lambda/3)}$ (read: the square root of the cosmological constant over three) and approaches it as the epoch grows without bound, so the scale factor does not become infinite at a finite time and the event horizon does not close in (derived given the constancy of $\Lambda$ and the Friedmann equation).

Part two, what a constant term does to a bound structure. A structure bound now is bound in a geometry that already contains $\Lambda$ at its present value, and $\Lambda$ has that value at every later epoch, so the part $\Lambda$ plays in the balance of the structure is the same at every later time (derived). For a

spherical mass the outward effect is one fixed effect, given by the Kottler geometry (reported). So a constant term unbinds no planet from its star, no star from its galaxy and no galaxy from its group (derived given the identification, with the reported Kottler geometry for the spherical case). For a planet, a molecule or an atom, what holds it together acts on matter whose forms are fixed while the six are held and whose kinds have the same attributes at every time, so the balance that sets its size is the same at every later time (derived given the identifications on which the hold rests and the structure of the kinds).

The scope of the answer: it covers the cosmological constant of our epoch and every structure bound within that epoch, from groups of galaxies to atoms. Within the collection's list of kinds, the sign of the sum of pressure and density for every state of the content is not argued; the answer's statement about the content rests on the closed list of field kinds and on the constant energy of the one scalar field. The collection does not compute the size of $\Lambda$'s fixed effect inside an atom; that size is computed in the table below from measured values.

| Reported or measured value | Primary source |
|---|---|
| A rip happens for w below minus one; for $w = -3/2$ and $H_0 = 70$ kilometers per second per megaparsec the paper places the end 22 billion years from now, with clusters erased about a billion years before it, the Milky Way about 60 million years before it, and atoms about $10^{-19}$ seconds before it. | Caldwell, Kamionkowski and Weinberg (2003) |
| For w exactly minus one the outward push inside a fixed volume does not grow, and "any system that is currently gravitationally bound ... will herafter remain so" (spelling as printed in the arXiv text). | Caldwell, Kamionkowski and Weinberg (2003), arXiv text |

| | |
|---|---|
| The Milky Way's total mass $M_{200} = 1.08\ (+0.20, -0.14) \times 10^{12}$ solar masses; with $\Lambda$ from the Planck values, the outward acceleration of $\Lambda$, $\Lambda c^2 r/3$, is 0.0069 of the inward acceleration $GM/r^2$ at the halo's edge $R_{200} = 217$ kiloparsecs (computed), a fixed share that does not grow. | Cautun and others (2020); Planck Collaboration, Aghanim and others (2020) |
| In the hydrogen atom, the outward force of $\Lambda$ on the electron at the Bohr radius is $1.9 \times 10^{-69}$ of the electric force (computed from the Bohr radius and the Rydberg energy). | Mohr and others (2025), CODATA 2022; Planck Collaboration, Aghanim and others (2020) |

The measured equation of state of the dark energy is set out in Appendix B.

## Chapter 4. Could Empty Space Change Its Nature?

The answer: the vacuum of the internal geometry has one held configuration and its hold ends only where the conditions of compactification fail, at the end of an interior, which is the turn and not the decay of a false vacuum; and on the collection's own arguments the potential of the one Higgs doublet has a floor which, at the order the collection derives, is the present vacuum, with no second scalar direction and no second, lower vacuum along the doublet, so the vacuum of our epoch is the only one of its kind and ends only where every epoch ends.

The criterion is reported: a vacuum decays by tunneling only if there is a second held configuration of lower energy for a bubble to lead to (Coleman and De Luccia 1980, as *The Compactification*, Chapter 2, Section VII, reports it). Chapter 4 has two parts, because the vacuum of the internal geometry (the context) and the vacuum of the Higgs field (the content) are different things. The condensate of the Higgs field is a value on the content instance of the internal space, and not a position among moduli (*The Kinds of Particle*, Chapter 3, Section VI; *The Compactification*, Chapter 2, Section VIII; derived).

## The vacuum of the internal geometry

| Ground | Where it is argued | Standing |
|---|---|---|
| Each factor of the internal space is homogeneous, and each homogeneous factor carries one invariant metric up to scale, so exactly two moduli remain: the volume and the shape. | *The Compactification*, Chapter 2, Section III; homogeneity from *The Gravitational Passage*, Chapter 9, Section II. | identification (homogeneity) joined to a theorem (Schur's lemma) |
| Both moduli are fixed at one point by the Einstein condition at the modal boundary, with the ratio of the radii $\sqrt{6}$ (read: the square root of six); the size is fixed in Planck lengths, the unit that the measured strength of gravity sets. | *The Compactification*, Chapter 2, Section IV; *The Gravitational Passage*, Chapter 11, Sections II and IV. | derived given the identification at the modal boundary; $\sqrt{6}$ a structural value |
| The floor that holds the space rests on the third axiom with the uncertainty relation. | *The Compactification*, Chapter 2, Section V. | derived |
| The action is built from the metric alone, so there is no flux and no flux integer, and the landscape of flux vacua has no counterpart; of a field of its own on the internal space, *The Gravitational Passage* states that its coupling "would be a second constant beside GN. This book takes no such field". | *The Compactification*, Chapter 2, Section VI; *The Gravitational Passage*, Chapter 12, Section VIII, Questions. | derived, from the action of the metric alone, whose choice the book states with its reason |

| | | |
|---|---|---|
| A first-order computation finds the derived point "a stable minimum, the only one in shape between $\sqrt{3}$ and $\sqrt{12}$", with its barrier past the modal boundary; every minimum in size lies above 1.48 Planck lengths; toward larger size the energy rises to zero with no barrier (*The Weight of Possibility*, Chapter 6, Section I); the hold does not rest on this computation. | *The Compactification*, Chapter 2, Section VII; *The Gravitational Passage*, Appendix D. | the book's standing "computed" |
| One internal space is reached by two routes that start from different premises: the algebra route (*Non-Commutative Geometry and the Immanent Metaphysics*, Theorem 12.1, under its postulates) and the geometry route (*The Gravitational Passage*, Chapter 9, Section VII, the only compact homogeneous product meeting the conditions, under its identifications); neither selects the space from a set of candidates. | *The Compactification*, Chapter 2, Section IX; *Side by Side*, Volume Two, "The Structure and the Act", Section VI; uniqueness also in *The Kinds of Particle*, "The Space of States", Section II, and *The Concept Sequence*, entry 25.18. | derived |
| The hold ends where its conditions fail, and in the new epoch the product re-forms with the same internal topology and the same radii in Planck units. | *The Compactification*, Chapter 2, Section VII; told again in *What the Beginning Left Behind*, Chapter 5, "Nowhere to Tunnel", and *The Concept Branches*, L-VI. | derived given the compactification conditions |

*The Compactification* states the result in the opening of its second chapter: "The hold ends only where the conditions of compactification fail, at the end of an interior, and that end is the turn of Chapter 1, not the decay of a false vacuum".

## The vacuum of the Higgs field

| Ground | Where it is argued | Standing |
|---|---|---|
| On the triple of non-commutative geometry, a scalar lives on the one edge that the finite Dirac operator crosses and on no other; no field enters but spinor fields, gauge one-forms and the Higgs doublet. | *Non-Commutative Geometry and the Immanent Metaphysics*, Chapter 19, Section VI, Proposition 19.10, with Proposition 19.7(iii). | derived (a theorem on the triple) |
| By the argument from comparison there is no second scalar: none on another edge, no second copy on the same edge, no colored one. | *Geeze, Wublets, and the Higgs*, Level 12, Section II, retelling *The Story of the Particles*, Level 8, Section II. | derived (the third axiom with the content/context partition) |
| The spectral action fixes the form of the potential: $V(\Phi) = -\mu^2\|\Phi\|^2 + \lambda\|\Phi\|^4$ (read: the potential equals minus mu squared times the squared size of the field, plus lambda times the fourth power of its size), one negative quadratic term and one positive quartic term. | *The Concept Branches*, E-I; source *Non-Commutative Geometry and the Immanent Metaphysics*, Chapter 13, Section III. | derived (the heat-kernel expansion of the spectral action, as reported there) |
| The self-coupling at tree level is $\lambda = a^2/2$ with $a = 1/2$, so $\lambda = 1/8$, positive on both routes (the form route and the share route). | *The Measures of the Kinds*, Chapter 13, Sections II and IV; told in the first person in *What the Beginning Left Behind*, Chapter 5, "The Vacuum of the Content". | derived given the stated identification $\lambda = a^2/2$; 1/8 a structural value |

| | | |
|---|---|---|
| The ground state does not keep the symmetry of the laws, by the Incommensuration Theorem, so the floor lies away from zero field. | *The Story of the Particles*, Level 8, Section III; *The Connes Correspondence*, Chapter 12, Section 3.3. | derived |
| The set of lowest states is the three-sphere, one connected piece, so moving among them lowers no energy. | *The Compactification*, Chapter 7, Section IX. | reported (topology of the one doublet) |
| The potential is bounded below, by the rule that every way of varying has a least state. | *The Measures of the Kinds*, Chapter 13, Section VI; told again in *The Concept Branches*, E-V. | reported (held as a rule; the premise "Hamiltonian bounded below" of the CPT theorem in *The Branches of the Kinds*, Chapter 3, Section III) |
| The collection's own correction to the self-coupling at the weak scale is positive and is not produced by the running of a coupling. | *The Measures of the Kinds*, Chapter 13, Section VI, as *What the Beginning Left Behind*, Appendix A, reports it. | the book's standing "a measured agreement" |

The steps. The only scalar field is the one doublet (derived, on two independent grounds). Along the doublet, the only direction in which a lower vacuum could lie is the size of the field, since the valley of lowest states is one connected set (derived, with the topology reported). In the variable $x = |\Phi|^2$ (read: x is the squared size of the field, which cannot be negative) the potential is $-\mu^2 x + \lambda x^2$, a parabola that opens upward when $\lambda$ is positive; its one minimum is at $x = \mu^2/(2\lambda)$, the ring of the present condensate; its value at zero field is higher; and it rises without limit beyond the minimum (derived, with only $\lambda > 0$ used). So at the order of the form the spectral action gives, and at the weak scale where the collection's self-coupling holds, the floor is the present vacuum and there is no

second, lower vacuum along the doublet, and the collection's arguments supply nothing for the present vacuum to tunnel into (derived, given the stated identification for the value 1/8; the sign of the quartic term is also given by the form).

The scope of the answer. The collection holds the running of the self-coupling in form and does not compute it from its own weak-scale values out to field values far above the weak scale; it makes no claim about the result of that running. *The Compactification* states its own scope in these words: "This chapter makes no claim about the stability of the content's vacuum under such running". The one computation of that running the collection reports is the Standard Model computation with measured inputs, given in the table below.

| **Reported or measured value** | **Primary source** |
|---|---|
| A classical field theory can have two stable homogeneous ground states, only one of which is an absolute minimum; in the quantum theory the higher one is a false vacuum, unstable by barrier penetration. | Coleman and De Luccia (1980) |
| The running self-coupling at the top quark's mass, in the MS-bar scheme at next-to-next-to-leading order, is $\lambda(M_t) = 0.12604$, from the measured masses (the tree value $1/8 = 0.125$ lies below it; *The Measures of the Kinds* gives the excess its standing as a measured agreement). | Buttazzo and others (2013) |
| Run with the Standard Model and measured inputs, the self-coupling crosses zero at a scale of about $10^{10}$ GeV, with an exact zero at about $10^{10}$ to $10^{12}$ GeV, and the electroweak vacuum is metastable. | Buttazzo and others (2013) |
| The lifetime of the electroweak vacuum in the Standard Model is about $10^{139}$ years, and more than $10^{58}$ years at 95 percent confidence. | Andreassen, Frost and Schwartz (2018) |

| | |
|---|---|
| Newton's constant G = 6.67430(15) × $10^{-11}$ cubic meters per kilogram per square second; the Planck mass is 1.22 × $10^{19}$ GeV (computed from G). | Mohr and others (2025), CODATA 2022 |

## Chapter 5. What Becomes of the Stars and Their Ashes?

The answer: a white dwarf is held up by the exclusion of its electrons, and a neutron star by the exclusion of its neutrons with the push of the force between nucleons, and none of these needs heat; its protons and electrons do not decay and its neutrons stay neutrons, so each remnant cools and keeps its mass and its particles until its path ends inside a black hole or carried away alone, where the six are no longer held, its matter stops being matter in this epoch's form, and its content does not cease.

| Ground | Where it is argued | Standing |
|---|---|---|
| The exclusion principle, derived from the principle of identity, with the physics of a filled sea of fermions: a pressure that needs no heat. | *The Matter We Know*, Volume Two, Chapter 13, "Matter Pressed Together", Chapter Overview and Sections II and III; exclusion from *The Matter We Know*, Volume One, Chapter 1, Box 1.2. | derived, given the reported physics of a filled sea of fermions |
| A neutron star is held up by its neutrons' exclusion and by the repulsive core of the force between nucleons. | *The Matter We Know*, Volume Two, Chapter 13, Section VI. | derived (exclusion); reported (the force between nucleons) |
| Heat flows from hotter to colder, so a remnant cools toward the temperature of its surroundings. | *The Matter We Know*, Volume Two, Chapter 2, Section VII. | derived (the counting of microstates) |

| | | |
|---|---|---|
| Neutrons in squeezed matter do not decay, because every electron state up to the Fermi energy is full. | *The Matter We Know*, Volume Two, Chapter 13, Section V. | derived given a measured input |
| Neutrons in the nuclei on the valley floor do not decay, because beta decay would raise the mass. | *The Matter We Know*, Volume One, Chapter 5, Section V. | derived given measured atomic masses |
| The gauge group is a product of three factors; no gauge boson carries both color and electroweak labels, so every operator that changes baryon number has a zero coefficient. | *The Branches of the Kinds*, Chapter 2, "The Stable Proton", Chapter Overview, Sections I and II, Boxes 2.1 and 2.2; told again in *The Matter We Know*, Volume One, Chapter 3, Section V; *The Concept Sequence*, Chapter 42; *Side by Side*, Volume One, the Sealed Record, Prediction 33. | derived (by two independent routes: the isometries of the space of states and the unitaries of the finite algebra), with one measured input |
| The channels other frameworks add are closed: no tower of states on the content instance, and the excitations of the context couple to content only through gravity, which carries no color and no weak label. | *The Branches of the Kinds*, Chapter 2, Section III. | derived |
| The electron is stable if it is the lightest charged particle; nothing lies below it among the charged leptons. | *The Branches of the Kinds*, Chapter 2, Section IV. | derived given a measured input (structural within its sector) |

| | | |
|---|---|---|
| Every bound structure ends in a black hole, and what it does not take in departs. | *The Gravitational Passage*, Chapter 18, Section III; told again in *At the Edge of Reality*, Chapter 12, and *The Matter We Know*, Volume Two, Chapter 13, Section VII. | reported |
| A remnant pressed beyond what its pressure holds becomes a black hole; a white dwarf drawn toward its greatest mass by a partner blows apart. | *The Matter We Know*, Volume Two, Chapter 13, Sections IV and VII, Box 13.2. | derived (the greatest mass); reported (the explosion) |
| The glow of black holes is real and far slower than the emptying. | *The Gravitational Passage*, Chapter 18, Section X. | reported |
| At the end of an interior, and for a body carried away alone, the conditions that hold the six compact fail; the forms of matter are no longer locked in, and the content does not cease. | *The Gravitational Passage*, Chapter 18, Sections VI and VII and Questions; told again in *At the Edge of Reality*, Chapter 13. | derived (the third axiom with the principle of comparison and the modal boundary) |
| From a black hole's interior the form of the content passes the turn, and no count passes. | *The Gravitational Passage*, Chapter 18, Sections VIII and XIII. | derived given the premise that the new context has no prior identity and the identification of the restoration with the Big Bang |
| The dark matter acts on ordinary matter only through gravity, so it does not heat a white dwarf by capture. | *The Weight of Possibility*, Chapter 4, Section II. | derived given the identification of the dark matter as a vibration of context |

The steps. *The Matter We Know* states the support in one sentence: "The crowd pushes back with a pressure that needs no heat at all, the degeneracy pressure, which falls as one over the particles' mass, so in a white dwarf it is the electrons that hold the star up (Box 13.1)". The cold remnant keeps its size (derived). *The Branches of the Kinds* states the stability of the proton: "A vertex that violates baryon number requires a mediator carrying both; since no such mediator exists, the coefficients of all baryon-number-violating operators vanish, and no decay of the proton through such an operator exists". That covers processes of one nucleon and of two nucleons together (derived), with one measured input: that the proton is the lightest whole of baryon number one. The electron does not decay (derived given the measured input that nothing of another kind lighter than it carries its charge). The neutrons stay neutrons, inside nuclei and in squeezed matter (derived given the two measured inputs in the table). So, left to itself, a remnant keeps its mass and its particles, goes cold and stays held up (derived from the steps before). Each remnant's path ends inside a black hole or carried away alone (reported for the clumping and departing; derived for there being exactly these two ends), and at either end its matter stops being matter in this epoch's form while its content does not cease (derived).

The rival account, in its own terms: Adams and Laughlin (1997) take as their working case a proton that decays, as grand unified theories predict, and follow a white dwarf powered by that decay as it loses mass, expands and ceases to be a star, and a neutron star that comes to resemble a white dwarf; they also describe dark matter captured in a white dwarf and annihilating there. The collection agrees with them on what holds each remnant up and on the two ends of its path, and it parts from them at the decay of the proton and at the capture of dark matter, for the reasons in the table.

The scope of the answer: it covers white dwarfs and neutron stars from their formation to the end of their paths. Which share of remnants takes each path is reported physics (Adams and Laughlin 1997) and is not argued in the collection. Fusion by tunneling among the nuclei of a cold

white dwarf is not argued in the collection; it is reported physics, given in the table (Caplan 2020). The zero-temperature electroweak sphaleron is stated as exponentially suppressed and unable to decay a single proton (*The Branches of the Kinds*, Chapter 2, Section III); its action among the many nucleons of cold dense matter is not argued. Whether the content of a remnant carried away alone re-emerges in the one new epoch that the interiors share is not argued in *The Gravitational Passage* (Chapter 18, Questions).

| Reported or measured value | Primary source |
|---|---|
| No proton decay seen: $\tau/B(p \to e^+\pi^0) > 2.4 \times 10^{34}$ years and $\tau/B(p \to \mu^+\pi^0) > 1.6 \times 10^{34}$ years at 90 percent confidence (read: the lifetime divided by the share of decays into a positron or a muon and a neutral pion exceeds the value given). | Takenaka and others, Super-Kamiokande (2020) |
| No electron decay seen: $\tau \geq 6.6 \times 10^{28}$ years at 90 percent confidence for $e \to \gamma\nu$. | Agostini and others, Borexino (2015) |
| Proton mass 938.27208943(29) MeV; neutron mass 939.56542194(48) MeV; electron mass 0.51099895069(16) MeV; energy of neutron decay 0.782 MeV (computed). | Mohr and others (2025), CODATA 2022 |
| The beta-decay Q-values from Z to Z + 1 of the nuclei of a white dwarf are all negative: helium-4 −22.9 MeV, carbon-12 −17.34 MeV, oxygen-16 −15.41 MeV, neon-20 −13.89 MeV, magnesium-24 −13.14 MeV (computed from the tabulated mass excesses). | Wang and others (2021), AME 2020 |
| In beta-stable nucleon matter at 0.204 nucleons per cubic femtometer the proton fraction is 0.073, which gives an electron Fermi energy of about 150 MeV (computed), about 190 times the 0.782 MeV of neutron decay. | Akmal, Pandharipande and Ravenhall (1998) |
| About 1 to 10 percent of the stars of a galaxy fall to the central black hole; the remainder are evaporated from the galaxy. | Adams and Laughlin (1997) |

| | |
|---|---|
| The lifetime of a hole of one solar mass is about $10^{66.3}$ years and of ten solar masses about $10^{69.3}$ years (powers computed from the published formula); the emptying by galactic dynamics comes within $\eta \approx 19$ to 25. | Page (1976); Adams and Laughlin (1997) |
| If the proton does not decay, isolated dwarfs above about 1.2 solar masses collapse after a delay of about $10^{1100}$ years set by fusion by tunneling, the fate of about $10^{21}$ stars. | Caplan (2020) |

## Chapter 6. What Happens to Someone Who Is Still There?

The answer: an observer in this physics is anything that compares; every observer ends at the end of a black hole's interior or carried away alone, and in both places nothing is left to compare against, so "not rotating" and "before and after" between distant things lose their footing while the one-way order inside each comparison stays; time does not stop, and the turn is not an event in time, so the end of the sky is the end of what an observer can compare with and not the end of time.

The collection defines an observer, or comparer, as anything that makes a comparison; *The View from Inside* states of the word: "The word names a position inside the world, and not a mind". The same use holds in *Category Theory and the Immanent Metaphysics*, Chapter 1, and *What Cannot Be*, Chapter 14, "Three Kinds of Time".

| Ground | Where it is argued | Standing |
|---|---|---|
| Inertia is a comparison: a standard of rest is fixed only by content there to compare it against, since a difference no comparison registers is no difference. | *At the Edge of Reality*, Chapter 13, "Frames Need Something to Compare Against", from Chapter 8; *The Gravitational Passage*, Chapter 18, Section IV. | derived given the principle of comparison |

| | | |
|---|---|---|
| Every observer meets one of two fates: the end of an interior, or carried away alone with no reference but its own horizon. | *The Gravitational Passage*, Chapter 18, Section IV; *At the Edge of Reality*, Chapter 13, "The Reference Unpins"; *The View from Inside*, Chapter 16, "Nowhere Else to Be". | derived (from the reported clumping and departing) |
| Time loses its large-scale direction where the distant reference is gone; the one-way order inside each act of comparison is not reversed. | *The Gravitational Passage*, Chapter 18, Section IV; *At the Edge of Reality*, Chapter 13, "The Reference Unpins"; *What the Beginning Left Behind*, Chapter 1, the fourth step. | derived given the principle of comparison |
| Both conditions that hold the six compact fail at the end of every interior and for a body carried away alone, and the third axiom excludes content without a context. | *The Gravitational Passage*, Chapter 18, Section VI; *At the Edge of Reality*, Chapter 13, "Both Conditions Fail" and "A Body Carried Away Alone". | derived |
| The end of an interior comes after a finite time on the clock of a body that falls in, as a limit; it lies after every moment of the interior and at no moment of the exterior; the release of a lone body is ordered before, at or after no event elsewhere. | *The Gravitational Passage*, Chapter 18, Section I and Questions; *At the Edge of Reality*, Chapter 13, "A Body Carried Away Alone". | reported (results of general relativity), with the placement derived |
| The turn is a limit approached from two sides; no comparison registers it as an event, and duration, temperature and rate do not apply to it. | *The Gravitational Passage*, Chapter 18, Section VIII; *At the Edge of Reality*, Chapter 16, "One Process, Two Sides", and Chapter 17, "No Comparison Across the Turn". | derived given the principle of comparison |

The steps. *At the Edge of Reality* joins the two fates in one sentence: "So every observer meets one of two fates". In both fates there is no comparable distribution of mass and energy against which a standard of rest could be defined, so the Mach principle fixes no frame (derived given the principle of comparison). The order of before and after across the outside world, and of cause and effect between distant events, rests on the reference of the distant matter, so it loses its support with that reference, while the one-way order inside each comparison stays as it is (derived). On the question whether time itself ends: the language of time applies to the approach on each side of the turn, and *At the Edge of Reality* states that "Duration, temperature and rate apply to the approach on each side; none of them applies to the turn". So the turn is no moment at which time stops (derived given the principle of comparison). On the clock of a body that falls into a black hole, the end of the interior comes after a finite time, as a limit: for a hole of the Sun's mass, at most about fifteen microseconds after the crossing, as *At the Edge of Reality*, Chapter 1, reports (reported: general relativity and the singularity theorems). At that limit the smooth description of space and time reaches its edge; no clock records a last tick beyond which it ticks no more, and the end lies at no moment of the outside world's time (derived, with the results of general relativity reported).

The scope of the answer: it covers every comparer of our epoch, of any material; it speaks of a mind only in Chapter 7. It states what is lost at the two ends, the reference for rest and the large-scale order of time, and what stays, the one-way order inside each comparison and the content itself.

## Chapter 7. Can a Mind Keep Thinking for Ever?

The answer: in this physics a thought is a real comparison with something else, made by a physical thinker, and the emptying leaves every thinker, whatever its store of energy, at the end of an interior or alone with nothing outside to compare against, where the forms its own matter takes are no longer held, so no one thinker thinks for ever; and the emptying

cannot come to rest, the turn restores a world with the same structure, and comparison happens again there, so thinking does not end, though no thought, record or count passes from one epoch to the next.

A note on words. The collection uses "observer" and "comparer" for anything that compares; where this section speaks of a mind it says "mind" or "thinker", and it means a comparer that is a conscious being in the sense of the second row below.

| Ground | Where it is argued | Standing |
|---|---|---|
| Every comparison carries the bound triple: a stance, a direction from act to record, and an outcome nothing before it fixed. | *What Cannot Be*, Chapter 22, "Why No Computation Is Everything", "The Bound Triple, Again". | derived (the Incommensuration Theorem) |
| The bound triple taken whole, as one act happening, is consciousness. | *What Cannot Be*, Chapter 22, "The Bound Triple, Again". | identification |
| A thinker thinks as a physical process making comparisons in the world, with an inside, and never as a program; a person is not a file. | *What Cannot Be*, Chapter 22, "What Computation Can Do" and "A Person Is Not a File". | derived (the Incommensuration Theorem) |
| The stance is continuous and situated. | *Measurement*, Chapter 14, Section VII. | derived (the Incommensuration Theorem) |
| Every comparison needs all six intrinsics, among them an objective target and a context; energy is the capacity of a system to take part in comparisons. | *Comparison; The Necessary Basis*, Chapter 4, Section III. | derived (the analysis of comparison); energy as a compound of the six is an identification |

| | | |
|---|---|---|
| The smallest comparison needs a reference other than the comparer, a bound structure to keep the record, and a signal between them. | *Why the Quantum Is the Way It Is*, Chapter 2, "Five Particles in an Empty Universe"; source *Comparison; The Necessary Basis*, Chapter 4, Section VI. | derived (a model built by construction and checked by subtraction, with reported atomic physics) |
| Time comes with comparison; felt time goes with the number of changes and with how much is new. | *What Cannot Be*, Chapter 14, "Three Kinds of Time", "Three Times". | derived (event time); reported (felt time, stated there without derivation) |
| Every observer's comparable exterior empties, and every observer meets one of two ends. | *The Gravitational Passage*, Chapter 18, Sections III and IV. | reported, with the two ends derived |
| At both ends the form of the thinker's own matter is no longer held. | *The Gravitational Passage*, Chapter 18, Section VI. | derived given the third axiom applied to the product geometry |
| The emptying cannot come to rest. | *The View from Inside*, Chapter 16, "Context Must Be Restored". | derived (the Incommensuration Theorem) |
| Every record raises entropy in the structure that holds it. | *What Cannot Be*, Chapter 13, "An Arrow Beneath the Arrow of Heat". | derived given a stated premise (the structural arrow joined with reported thermodynamics) |
| The fineness of a comparison depends on the energy brought to it. | *What Cannot Be*, Chapter 12, "The Two Edges of Comparison". | derived given the identification of Planck's constant as the inner edge of comparison |
| Determinism is impossible. | *Measurement*, Chapter 14, Section II. | derived (the Incommensuration Theorem) |

| | | |
|---|---|---|
| No signal reaches beyond the boundary of comparison. | *Measurement*, Chapter 14, Section IV. | derived given the identification of c as the boundary of the domain of comparison |
| The derived structure is the same in every epoch; no act spans the turn. | *At the Edge of Reality*, Chapter 20, "What Carries Over"; *The Gravitational Companion*, "Two Formal Triples of a Domain", Section III. | derived given the identification of the restoration with the Big Bang |

What a thinker needs. *What Cannot Be* states of stance, direction and remainder: "None of the three is present without the other two". *Comparison; The Necessary Basis* states: "Energy is the capacity of a system to participate in comparisons". So a store of energy, however large, is a capacity, and a capacity is used only where there is something actually there to compare with (identification for energy; derived for the need of a target and a record).

What the emptying leaves. Every thinker belongs to some bound structure and meets one of the two ends (reported, with the two ends derived); at both, nothing outside can be compared with and the forms the thinker's own matter takes are no longer held (derived given the principle of comparison and the third axiom). So no thinker makes an unending run of findings, and this conclusion uses neither the size of the store, nor the temperature, nor the rate of thinking (derived given those premises).

Dyson and Krauss and Starkman, set beside the account. Dyson (1979), working in an open universe with no cosmological constant, held that a society which thinks more slowly as it cools, and hibernates for a growing share of the time, lives through an unbounded subjective time on a finite store of energy. Krauss and Starkman (2000), taking a positive constant, replied that every observer then has a horizon and a finite store, that the horizon's temperature is a floor, that hibernation and its alarm clocks fail, and that no finite system performs infinitely many computa-

tions. On the horizon, the account agrees with Krauss and Starkman, on its own ground that content beyond the horizon cannot be compared with the observer in principle (reported, with the criterion derived). On the temperature floor, the account states that the outside radiation thins toward the horizon's own temperature (reported); the cost of cooling below that floor is not argued in the collection. On Dyson's scaling hypothesis, the account allows a thinker built for a lower temperature, and it holds that a copy matching the original part for part is not shown, by the match, to be the same subject, "because being a person is not exhausted by any exterior description" (*What Cannot Be*, Chapter 22, "A Person Is Not a File"; derived). On what is counted, the account counts a thinker's life in findings, each a real comparison, and its limit is the loss of anything to compare against, not a limit on a count of operations (derived). Where the counts meet is the record: "A record is itself a change that cannot be undone, and making a record raises the entropy of the instrument that holds it" (*What Cannot Be*, Chapter 13, "An Arrow Beneath the Arrow of Heat"), which meets Krauss and Starkman's point about heat (derived given the stated premise for the entropy of recording). On the alarm clock, a clock that wakes with certainty after every one of unboundedly many sleeps would be a deterministic process, and *Measurement* shows that "no world is purely and completely deterministic" (Chapter 14, Section II); a sleeper whose clock does wake it still wakes, at the end, with nothing outside to compare against (derived given the stated identification of a certain clock with a deterministic process). On analog memory, reading a continuous quantity to ever more digits needs ever more energy for each reading (derived given the stated identification). On communication, no chain of relays reaches beyond the event horizon of the society that sends (derived given the stated identification). On escape through black holes, *The Gravitational Companion* states: "No comparison registers the turn as an event, so no act spans it, and no finding made in one epoch is real in the other" ("Two Formal Triples of a Domain", Section III); so a thinker does not pass into the next epoch as a thinker (derived given the identification of the restoration with the Big Bang). On Dyson's first question, whether the

universe freezes into permanent quiet, the account also answers no, on the ground that a final featureless emptiness is excluded by the Incommensuration Theorem (derived).

The next epoch. The turn restores a large world with the same derived structure; the new epoch makes stars, and the stars make black holes; comparison happens there, and every comparison carries the bound triple, so comparers are present in the next epoch as in ours (derived given the identification of the restoration with the Big Bang). No finding, record or count of a thinker of our epoch is real in the next (derived given the same identification).

The scope of the answer: it covers every thinker that is a physical comparer within one epoch of an accelerating universe, and thinking across epochs in the sense of the same structure and the same conditions in each. The collection derives no biology, so the arising of minds in the next epoch is not argued; what the collection establishes is that the next epoch begins with the same structure and the same clean slate under which minds arose in ours. The collection states what carries across one turn and makes no claim about a completed totality of all epochs (*The Gravitational Companion*, "Two Formal Triples of a Domain", Questions). Which limit a thinker meets first on its own clock, the exhaustion of its store or one of the two ends, depends on the thinker's design; the answer does not depend on that order.

| **Reported or measured value** | **Primary source** |
|---|---|
| Dyson's conclusion for an open universe: "Life and communication can continue for ever, utilizing a finite store of energy", if his scaling laws hold; the free energy for indefinite survival of a society with the complexity of the present human species is of the order of $6 \times 10^{37}$ erg, about as much as the Sun radiates in eight hours. | Dyson (1979) |

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| Krauss and Starkman's conclusion for a universe dominated by a cosmological constant: "the integrated conscious lifetime of any civilization will be finite"; and "no finite system can perform an infinite number of computations". | Krauss and Starkman (2000) |
| A cosmological event horizon carries thermal radiation; its temperature is $T = \hbar H/(2\pi k_B)$ (read: the reduced Planck constant times the expansion rate, divided by two pi times Boltzmann's constant), which for the de Sitter horizon the epoch approaches, with $H_0\sqrt{\Omega_\Lambda} = 55.8$ kilometers per second per megaparsec, is about $2.2 \times 10^{-30}$ kelvin (computed from the Planck values). | Gibbons and Hawking (1977); Planck Collaboration, Aghanim and others (2020) |
| Normal star formation ends by $\eta \approx 14$, and stars evaporate from the galaxy at $\eta \approx 19$ to 20. | Adams and Laughlin (1997) |

## Chapter 8. Is the Long Emptying the End?

The answer: the emptying is not final, on three independent grounds, the third axiom (content cannot be without a context), the Incommensuration Theorem (a featureless emptiness everywhere the same would be perfectly symmetric and perfectly continuous at once, which no comparison finds), and the relativity of every count to a context (the entropy of the old epoch has nothing left to be counted against); the end of every black hole's interior is one end, and from it the ten-dimensional geometry restores a new large world, so the emptying ends in a turn and not in a final dark.

| Ground | Where it is argued | Standing |
|---|---|---|
| Ground A. The content does not cease at the end, and the third axiom excludes content without a context, so a context must form again from the ten-dimensional geometry that remains. | *At the Edge of Reality*, Chapter 16, "Content Needs a Context"; *The Gravitational Passage*, Chapter 18, Section VII. | derived |

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| Ground B. A final featureless emptiness would be perfectly symmetric and perfectly continuous at once, which the Incommensuration Theorem excludes, so the emptying cannot come to rest. | *The View from Inside*, Chapter 16, "Context Must Be Restored". | derived |
| Ground C. Every entropy is a count of the arrangements of a thing's parts that leave it looking the same from outside: the states that the comparisons available from a context cannot tell apart, always a count made against a context; at the turn the old context has ended, so no count carries over and each epoch begins its own count. | *The Compactification*, Chapter 3, "The Past Hypothesis at the Turn", Sections V and VII; *At the Edge of Reality*, Chapter 18, "Every Count Has a Context" and "The Old Objection to Cycles"; *The Gravitational Passage*, Chapter 18, Section VIII; the emptying at the end of an epoch, *The Compactification*, Chapter 5, Section VIII. | derived given the stated premise that an entropy is a count relative to a context |
| The ends of all black hole interiors are one. | *The Gravitational Passage*, Chapter 18, Section II; *At the Edge of Reality*, Chapter 11, "The Ends Are One". | derived given the principle of comparison and the stated premise that the new context registers no distinction of the old exterior |
| The restoration of context is the Big Bang of the new epoch; *At the Edge of Reality* states that the restoration "is therefore neither a creation from nothing, nor a fluctuation in a vacuum that was already there, nor a breakdown at which the equations fail and the description falls silent". | *The Gravitational Passage*, Chapter 18, Section VII; *At the Edge of Reality*, Chapter 16, "The Identification". | identification |

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|---|---|---|
| Collapse and origin are one transition, so the cosmological history is a cycle. | *The Gravitational Passage*, Chapter 18, Sections VIII and XII. | derived given the identification |

The steps. Ground A, in the words of *At the Edge of Reality*: "So a context must form again, and the only structure from which a new context can form is the ten-dimensional geometry that remains". Ground B, in the words of *The View from Inside*: "The emptying cannot simply come to rest. Context must be restored". Ground C answers the old fear of heat death on its own terms: heat death is a state of greatest entropy, and an entropy is a count reckoned against a context; when the context has emptied, the count has no reference left, and the new epoch reckons its counts against its own context (derived given the stated premise). The three grounds are independent: the first rests on the third axiom, the second on the Incommensuration Theorem, and the third on what an entropy counts. The new geometry has no prior identity, so it begins even up to the departures the Incommensuration Theorem requires, and the small gravitational count at the start of an epoch, which Penrose proposed as a separate principle (his Weyl curvature hypothesis), is reached here as a consequence (*At the Edge of Reality*, Chapter 18, "Even From the Start"; *The Compactification*, Chapter 3, Section VI; derived given the stated premise). The restoration is identified with the Big Bang of the new epoch (identification), and *The Gravitational Passage* draws the consequence for the whole history: "If black hole collapse and cosmological origin are one transition approached from its two sides, the cosmological history is a cycle, and not a single arc from Big Bang to heat death".

The scope of the answer: it covers the end of our epoch and the restoration of a context from it. The reset of the count is given by principle; *The Gravitational Passage* states that "The reset is given here by principle; a count of states across the turn, in numbers, is not given in this book". Whether the content of a body carried away alone re-emerges in the one new epoch that the interiors share is not argued in *The Gravitational Passage* (Chapter 18, Questions).

| Reported value | Primary source |
|---|---|
| The durations of the emptying and of evaporation, as in Chapter 1. | Krauss and Scherrer (2007); Adams and Laughlin (1997); Page (1976) |
| Black holes in orbit about each other merge: the first observed merger of two black holes, one of the three facts behind the identity of the ends (*The Gravitational Passage*, Chapter 18, Section II). | Abbott and others, LIGO Scientific Collaboration and Virgo Collaboration (2016) |

## Chapter 9. What Crosses Over, and What Stays Behind?

The answer: information has two senses, the form of the content (what the matter is and which alternatives it has taken) and a count of states relative to a context; the form of the content crosses the turn with the content, as one averaged form with no mark of the black hole it came through, and it appears in the new epoch as the first faint departures from uniformity, while no count, length, record or entropy crosses; the same law holds again in every epoch, and the shape and size of the six return; so what crosses is the form of the content, the law returns, and nothing crosses as itself.

| Ground | Where it is argued | Standing |
|---|---|---|
| Information has two senses: the form of the content, carried with the matter wherever it goes, and a count of states relative to a context. | *The Unquantized Arena*, Chapter 17, Proposition 17.3 (stated of a black hole); applied to the turn in *The Compactification*, Chapter 3, Section IX. | derived |

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| No count passes the turn; the form of the content passes with the content. | *The Compactification*, Chapter 3, Section IX; *The Gravitational Passage*, Chapter 18, Sections VIII and XIII; *At the Edge of Reality*, Chapter 18, "Information Is Not Destroyed". | derived given the stated premise that every count is relative to a context |
| No length, no record and no mark passes: the new outside world re-forms with no prior identity. | *What the Beginning Left Behind*, Chapter 21, "What Passed the Turn, and What Did Not"; *The Gravitational Passage*, Chapter 18, Sections VII and VIII. | derived given the stated premise that the new geometry has no prior identity |
| The form of the content passes as one form, undistinguished as to the interior it came from, because the only context that drew those distinctions has no moment at the end. | *At the Edge of Reality*, Chapter 18, "Information Is Not Destroyed"; *The Gravitational Passage*, Chapter 18, Section IX. | derived given the principle of comparison |
| The departures from uniformity of the new epoch are the form of the content, the old distinctions averaged and not erased. | *The Gravitational Passage*, Chapter 18, Section IX; *At the Edge of Reality*, Chapter 18, "Even From the Start". | identification |
| The derived structure is the same in every epoch: the shape of the internal space, the ratio of its radii and its size at the Planck scale; the product re-forms with the same internal topology. | *At the Edge of Reality*, Chapter 20, "What Carries Over"; *The Gravitational Passage*, Chapter 18, Section VII. | derived given the identification of the restoration with the Big Bang |

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|---|---|---|
| No act of comparison spans the turn. | *The Gravitational Companion*, "Two Formal Triples of a Domain", Section III; *What the Beginning Left Behind*, Chapter 21, "A Cycle with No First Turn". | derived (the formal triples of a domain) |

The steps. *The Compactification* states the division in two sentences: "In the second sense, the reset says that no count passes the turn. In the first sense, the form of the content does pass: the content is carried from the collapse to the emergence, and its form is carried with it". Information that falls into a black hole is therefore not destroyed; it is lost to every observer who stays outside the horizon, and it re-emerges as the departures from uniformity of the new epoch (derived given the stated premise, with the departures an identification). Of what returns, *At the Edge of Reality* states: "The structure that this account derives is the same in every epoch". On whether the constants change between epochs: the strength of gravity is the one scale the account takes from measurement, and a comparison of it in one epoch with its value in the next would be a comparison across the turn, which is not made; what any epoch measures is a ratio found within that epoch (*At the Edge of Reality*, Chapter 20, "What Carries Over"; derived).

The scope of the answer: it covers what crosses the turn from the end of the interiors, and what returns as the derived structure. Three matters the collection leaves to another account, in its own words: of the dimensionless ratios of the content, "whether they repeat from epoch to epoch is not fixed in this book" (*The Gravitational Passage*, Chapter 18, Questions); how the turn leaves the value of baryon number less lepton number belongs to the account of the turn (*The Coming of the Kinds*, "What Every Change Keeps", Section IV); and whether a mark of a single body of the previous epoch passes the turn is named as a question in *Side by Side*, Volume One, "The Registered Predictions Beside Roger Penrose", Section IV.

## Chapter 10. Could Anyone Escape?

The answer: no body, readable record, identity, person or message crosses from our epoch into the next as itself; what crosses is the form of the content of everything that fell into the black holes of our epoch, as one averaged form, and the same law holds again in the next epoch; and there is no other universe to travel to, because the next epoch is joined to ours by no path and no act, and whatever a path can reach belongs to our own one domain.

| Ground | Where it is argued | Standing |
|---|---|---|
| Information in two senses: the form passes the turn, the count does not. | *What the Beginning Left Behind*, Chapter 7, "Information in Two Senses"; source *The Gravitational Passage*, Chapter 18, Sections VIII and XIII. | derived |
| No length, record or mark passes; no geometry and no field pass. | *What the Beginning Left Behind*, Chapter 21, "What Passed the Turn, and What Did Not". | derived given the stated premise that the new geometry has no prior identity |
| Every ending is the same ending: the next epoch registers nothing of which black hole its content came from. | *At the Edge of Reality*, Chapter 11, "The Ends Are One". | derived given the principle of comparison and a first-person premise |
| No comparison registers the turn as an event. | *At the Edge of Reality*, Chapter 17, "No Comparison Across the Turn". | derived (reported results of general relativity, with the principle of comparison) |

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|---|---|---|
| No act spans the turn, and no record of one epoch is ever set beside a record of the other. | *The Gravitational Companion*, "Two Formal Triples of a Domain", Section III; told again in *What the Beginning Left Behind*, Chapter 21, "A Cycle with No First Turn". | derived (the formal triples of a domain) |
| No domain contains every domain. | *The Gravitational Companion*, "Two Formal Triples of a Domain", Section III. | derived (the Incommensuration Theorem) |
| The universe, as a domain, has no outside. | *Comparison; The Necessary Basis*, Chapter 12, Section I. | identification (domain, relation and identity as a foundational triple) |
| To say that many worlds exist applies existence outside its range; many worlds are real. | *An Immanent Metaphysics*; told again in *Comparison; The Necessary Basis*, Chapter 12, Section V. | derived (the definitions of existence and of being) |
| Events outside the cone of an event are no places at all; space is the pattern of causal connection. | *What Cannot Be*, Chapter 12, "The Shape of What Can Reach What", "Beyond the Farthest Point". | derived given the identification of space with the pattern of causal connection |
| The matter of people is a passing feature of the epoch. | *At the Edge of Reality*, Chapter 13, "The Form of Matter Is Not Held". | derived given inertia as a comparison and the compactification conditions |
| Beyond a Cauchy horizon lies further geometric time, and no extension makes an earlier finding occur again. | *Why Time Travel Is Not a Concept*, Chapter 3, Section IV, Proposition 3.1; told again in *What Cannot Be*, Chapters 14 and 16. | derived |

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| The inside of a real black hole is expected to end, for every path within it, in a last moment taken as a limit (reached after a finite time on that path's own clock), and not in a place. | *What Cannot Be*, Chapter 14, "Singularities and the Planck Scale". | reported (the instability of the inner horizon), with an expectation stated as an expectation |
| A person is not a file. | *What Cannot Be*, Chapter 22, "A Person Is Not a File". | derived given the identification of the first-person stance as continuity with asymmetry |
| One vacuum: the hold ends where its conditions fail, not by tunneling. | *The Compactification*, Chapter 2, Section VII. | derived, with the first-order computation at the book's standing "computed" |
| The six are dimensions of possibility, which no comparison travels through. | *At the Edge of Reality*, Chapter 7, "Where the Six Are". | identification |
| A black hole run backward is a beginning, not a hole at the other end. | *At the Edge of Reality*, Chapter 17, "A Black Hole Run Backward". | derived (the Kasner arc) with the identification of the restoration with the Big Bang |
| The accelerating expansion does not stop the cycle. | *What the Beginning Left Behind*, Chapter 21, "What the Six Left Fixed". | derived given the identification of the constant as a property of the relation between an observer and its horizon |
| The arena has no quantum state. | *What the Beginning Left Behind*, Chapter 7, "Gravity Was Never Born", after *The Unquantized Arena*. | derived given the identification of gravity as the context of physics |

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|---|---|---|
| The other branches of a universal state exist and are not real for the comparer. | *Side by Side*, Volume One, "Sean Carroll, Many Worlds and Physics from Comparison", Section III. | derived (the definitions of existing and being real) |
| Identity is evaluated by comparison across contexts. | *Comparison; The Necessary Basis*, Chapter 12, Section I. | identification |

The steps. In this account the universe does not die in the sense the escape presupposes: each epoch ends in its black holes and turns into the next (derived given the identification of the restoration with the Big Bang and of the constant as a property of an observer's horizon). No body crosses as a body, because a body is matter in this epoch's form, with a size in a geometry, and none of these passes (derived given inertia as a comparison). What crosses is the form of the content, as one averaged form; the law is not carried across, it returns, and the same law holds again in the next epoch (derived). No record crosses as a record; *What the Beginning Left Behind* states: "No act of comparison spans the turn, so no finding made in one epoch is real in the other, and no record of one epoch is ever set beside a record of the other" (derived). No identity crosses, because finding something in the next epoch to be the same as something in ours would be a comparison across the turn (derived given the identification of identity with the transcendent modality). No person crosses, as a body or as information (derived given the stated identification). There is no other universe to escape into (derived given the identification of space with the pattern of causal connection and of the domain with the omniscient modality). The reason is that if a journey reaches a region, then that region is part of our one domain, and if no journey reaches a region, then nothing reaches that region, and so nothing can escape into that region either.

Kaku's steps, in his own terms and beside the account. Kaku (*Parallel Worlds*, Chapter 11) asks for a theory that settles whether wormholes are stable, for natural wormholes and white holes, for probes through black

holes, for a baby universe made from a false vacuum, for the Planck energy, for warp drives and negative energy, and, as the last hope, for a seed of information that regrows a civilization on the other side. The account meets each at the point where it speaks: the arena has no quantum state to correct; nothing passes the turn as a gateway; a probe reaches the common end of all interiors, where its matter ceases to be matter of this epoch's form; there is one vacuum and no hyperspace for a baby universe to bud into; the younger and hotter worlds are the beginnings of epochs, at no moment of our time; whatever a wormhole connects lies in our own pattern of connection; and the form of the content of a seed that falls into a black hole crosses within the one averaged form, while the seed arrives as no message and the memories it carries are no persons (each derived, at the standings in the table).

The scope of the answer: it covers what crosses from one epoch into the next, what does not, and whether a passage to another universe can be made by any of the means Kaku names. Whether a wormhole can form within one epoch and be held open by negative energy is not argued in the collection; for escape into another universe the question does not arise, since whatever such a wormhole connects lies in our own pattern of connection. Whether the content of a body carried away alone re-emerges in the one new epoch that the interiors share is not argued in *The Gravitational Passage* (Chapter 18, Questions).

| **Reported or measured value** | **Primary source** |
|---|---|
| The constant is positive (share about 0.685), so every observer has a cosmological event horizon. | Planck Collaboration, Aghanim and others (2020) |
| The emptying by galactic dynamics comes within $\eta \approx 19$ to 25; holes of $10^9$ to $10^{10}$ solar masses, the final central masses Adams and Laughlin estimate, evaporate in $10^{93}$ to $10^{96}$ years (computed from Page's formula). | Adams and Laughlin (1997); Page (1976) |

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|---|---|
| Kaku's proposal of escape, in eleven steps, as a published proposal. | Kaku (2005), *Parallel Worlds*, Chapter 11, "Escaping the Universe" |

## Chapter 11. Has This Happened Before?

The answer: our epoch is one turn of a cycle with no first turn, and it differs from every other cycle on offer in where the turn between epochs lies and what it needs: the passage lies at the common end of the interiors of black holes and needs nothing to vanish, no contraction of the whole and no field whose energy turns negative, and across it no count passes, only the form of the content.

| Ground | Where it is argued | Standing |
|---|---|---|
| The turn is a limit that no comparison registers as an event; duration, temperature and rate do not apply to it. | *The Gravitational Passage*, Chapter 18, Section VIII; *At the Edge of Reality*, Chapter 16, "One Process, Two Sides". | derived given the principle of comparison, with the identification of the restoration with the Big Bang |
| The ends of all interiors are one, and the epochs follow one another in a single sequence. | *The Gravitational Passage*, Chapter 18, Sections I, II and XII; *At the Edge of Reality*, Chapters 11 and 20. | derived given the principle of comparison |
| What ends an epoch is the failure of the conditions that hold the six compact; the third axiom requires a new context. | *The Gravitational Passage*, Chapter 18, Sections VI and VII; *Side by Side*, Volume One, "Two Roads to Reality", Section V. | derived (the third axiom) |

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| Every observer's exterior empties under a continuing expansion. | *The Gravitational Passage*, Chapter 18, Section III. | reported |
| The constant is one constant, driven by no field, and it does not resist the collapse. | *The Gravitational Passage*, Chapter 13, Sections V and VI, and Chapter 18, Section XII. | derived given the identification of the accessible share |
| The new epoch is spatially flat. | *The Gravitational Passage*, Chapter 18, Section IX. | derived given the stated premise that the new geometry has no prior identity |
| Entropy is a count relative to a context, and no count crosses the turn. | *The Gravitational Passage*, Chapter 18, Section VIII; *The Compactification*, Chapter 3, Section VII; *At the Edge of Reality*, Chapter 18, "The Old Objection to Cycles". | derived given the stated premise that an entropy is a count relative to a context |
| The internal space has one vacuum, and the same internal space re-forms at the same radii in Planck units. | *The Compactification*, Chapter 2, Section VII; *The Gravitational Passage*, Chapter 11, Section II. | derived; the absence of a second minimum at the book's standing "computed" |
| On the Kasner arc the three shrink as the time remaining to the power 5/9 while each of the six grows as that time to the power $-1/9$; read away from the turn, the three grow and the six contract. | *The Gravitational Passage*, Appendix B, Section IV; *The Compactification*, Chapter 1, Section VI. | derived (the Kasner conditions); 5/9 and $-1/9$ structural values; the placement at the end point is the book's stated choice |
| What passes is the form of the content, registered as departures of one form, adiabatic and scalar at first order, with waves only at second order. | *The Gravitational Passage*, Chapter 18, Sections IX and XIII. | identification (the departures are the form); derived given it (adiabatic, scalar) |

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| The Incommensuration Theorem places at the turn the edge of every description, and it requires departures from perfect uniformity. | *The Gravitational Passage*, Chapter 3, Section IV, and Chapter 18, Sections VIII and XI; *At the Edge of Reality*, Chapter 15. | derived |
| The dark matter is made at the turn, ends at the turn, and does not decay within an epoch. | *The Weight of Possibility*, Chapter 1, Section II, and Chapter 4. | identification, argued, resting on a parity the book takes as gauged by the principle of identity, a step the book names as its own |
| Nothing travels through the six dimensions of possibility. | *Measurement*, Chapter 4, Section VII; *Side by Side*, Volume One, "Two Roads to Reality", Section VI. | derived (the locatedness of comparison) |
| The internal space is not a Calabi-Yau space: its first Chern class does not vanish. | *The Gravitational Passage*, Chapter 9, Section VIII. | derived (a fact of mathematics applied to the identified internal space) |

The cycle without a first turn. Each epoch begins its own count, so the cycle has no first iteration; *At the Edge of Reality* states: "Here no count is carried across the turn, for the matter or for the geometry, because each count is relative to the context that ends". Tolman's worry rests on the premise that the entropy of one cycle is carried into the next; this cycle denies that premise (derived given the stated premise about entropy).

Beside Penrose. Penrose's conformal cyclic cosmology joins the remote future of one aeon, after every black hole has evaporated, to the beginning of the next, by rescaling a four-dimensional geometry; for that, rest mass must be absent in the remote future, and his dark matter, the erebons, must decay within each aeon. The two accounts share six features, which *Side by Side*, Volume One, "Two Roads to Reality", Section V, lists: no first;

a state with nothing left to measure against; the joining of what cannot be told apart; a reset of the count of entropy; a role for the accelerating expansion; and dark matter of about the Planck mass made at the passage. They differ in six, in the same section: where and when the turn between epochs lies (the end of each interior, against the remote future of the whole); what must vanish, where *Side by Side* states that "The collection needs nothing to vanish: what fails at the end of an interior is the context"; the geometry (ten dimensions on the Kasner arc, against a rescaled four-dimensional geometry); how the two sides are joined (indiscernibility, against a matching condition); information (not destroyed, against destroyed); and the sky (departures of one form, no measurable first waves, and dark matter that does not decay, against circles and Hawking points in the microwave background).

Beside the bounce of loop quantum cosmology. *The Gravitational Passage* places itself beside that bounce by the statement that it too reaches a finite curvature at the Planck scale (Chapter 19, Section IV), while the collection constructs no geometry at the turn.

Beside the ekpyrotic and cyclic models. The rival accounts, in their own terms: in the ekpyrotic universe (Khoury, Ovrut, Steinhardt and Turok 2001) a brane drifts across a fifth dimension and strikes our brane, and the collision starts the hot expansion; in the cyclic model of Steinhardt and Turok (2002) the field that measures the distance between two branes rolls until its potential energy turns negative, expansion stops, a slow contraction follows and the branes collide, and the entropy of each cycle is diluted by the acceleration that precedes it; in the cyclic model of Ijjas and Steinhardt (2019) a scalar field's energy turns negative, a slow contraction follows, and a smooth four-dimensional bounce begins the next cycle, while the total entropy grows and the size of space grows faster. Set beside them on seven points. What ends an epoch: in this account no field ends it; it ends at the end of each interior, where the conditions that hold the six fail (derived). Whether the whole contracts: the exterior never contracts; what shrinks is the three large directions inside each interior (derived given the constancy of $\Lambda$ and flatness). What the transition is: a limit

with no duration, temperature or rate, against an event in a description that holds through it (derived given the Incommensuration Theorem and the principle of comparison). What carries entropy: no count crosses, against dilution (Steinhardt and Turok) or a growing total outgrown by space (Ijjas and Steinhardt) (derived given the stated premise about entropy). What extra dimensions do: the six are dimensions of possibility, held at a fixed size and released only when their context fails, with no bulk in which a brane could move; at the transition they grow on the approach and contract after it (derived). What passes: the form of the content, against fields and fluctuations carried through the bounce (derived given the identification of the departures). What each expects in the sky: here the departures are adiabatic and scalar, waves arise only at second order, space is flat, w is exactly minus one at every era so the acceleration never ends, and the dark matter does not decay; Steinhardt and Turok and Ijjas and Steinhardt expect the present acceleration to end.

The scope of the answer: it covers the structure of the cycle as the collection argues it and each of the seven points set beside the three rival models and beside Penrose's aeons. What carries an ordinary interior, whose six hold their size, onto the Kasner arc is not argued in *The Gravitational Passage* (Chapter 19, Section II); the comparison with the brane models uses the direction of change of the six on the arc. The collection does not fix the sign of the tilt of the departures (*The Gravitational Passage*, Chapter 18, Section IX), and it does not fix the temperature at which the reconstructed history of the new epoch begins (Chapter 18, Section XI).

| **Reported or measured value** | **Primary source** |
|---|---|
| The worry about cycles: entropy carried from cycle to cycle makes each larger and longer than the last. | Tolman (1934) |
| Conformal cyclic cosmology: aeons joined by conformal rescaling at the remote future. | Penrose (2010) |

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| Penrose gives the erebons a lifetime of perhaps about $10^{11}$ years, within each aeon. | Penrose (2018) |
| The ekpyrotic universe; the cyclic model; the new kind of cyclic universe. | Khoury, Ovrut, Steinhardt and Turok (2001); Steinhardt and Turok (2002); Ijjas and Steinhardt (2019) |
| Curvature share $\Omega_K = 0.001 \pm 0.002$. | Planck Collaboration, Aghanim and others (2020) |
| Non-adiabatic share of the variance of the microwave background temperature below 1.3, 1.7 and 1.7 percent (95 percent confidence) for the cold dark matter, neutrino density and neutrino velocity modes. | Planck Collaboration, Akrami and others (2020) |
| Ratio of tensor to scalar power $r(0.05) < 0.036$ at 95 percent confidence. | BICEP/Keck Collaboration, Ade and others (2021) |
| Spectral index $n_s = 0.9649 \pm 0.0042$. | Planck Collaboration, Akrami and others (2020) |
| Effective number of light species $N_{eff} = 2.99 \pm 0.17$; *The Compactification*, Chapter 7, takes its bound on the settling waves from this measured count. | Planck Collaboration, Aghanim and others (2020) |
| A decaying dark component is bounded to $f\Gamma < 6.3 \times 10^{-3}$ per billion years (read: the decaying fraction times the decay rate), a lifetime beyond about 160 billion years for the whole component. | Poulin, Serpico and Lesgourgues (2016) |

The coming measurements that bear on these chapters, and what this account says they will find, are set out in Appendix B.

# What the Coming Measurements Will Measure

This book's account makes definite statements about what instruments will find. The instruments of the coming decades will measure each quantity in those statements more closely than ever before. This appendix takes five of the statements, one in each section. A short last section says how this account counts a result. Each of the five sections first says what the coming measurement will measure and what this account says the measurement will find, then names the instruments that will make the measurement, and ends with what the measurements so far have found.

Three terms recur in every section. The *uncertainty* of a measurement is the range within which the true value most likely lies. The uncertainty is written $\pm$ and read "give or take". A *standard deviation* is the usual measure of how far a measurement might wander from the true value by chance. A result commonly lies one standard deviation away from the true value, but a result five standard deviations away from the true value would come by chance less than once in a million tries. A limit stated at *90 percent confidence* is a limit that the result of a search would have crossed nine times in ten, if the true value lay beyond the limit. A limit stated at 95 percent confidence is a limit that the result of a search would have crossed nineteen times in twenty, if the true value lay beyond the limit.

## The Energy of Empty Space at Every Era

The coming surveys will measure the equation of state of the energy that drives the accelerating expansion of the universe. The equation of state of an energy is the ratio of the energy's pressure to its *energy density*.

The energy density is the energy in each cubic meter. This account says that the surveys will find the equation of state to be exactly minus one, at every era of our epoch's history.

An observer's horizon is the boundary beyond which no event can ever send a signal to that observer. In this account the cosmological constant is the share of the energy of empty space that is open to a measurement made from inside the universe. The cosmological constant is a property of the relation between an observer and that observer's horizon (Chapters 1 and 2). The cosmological constant enters Einstein's equations of gravity as one constant term, the measurement made now fixes the constant once, and within the one space and time of our epoch the cosmological constant cannot vary. When an energy does not vary as the universe grows, the energy's equation of state is exactly minus one, so the equation of state of the cosmological constant is exactly minus one at every era of our epoch.

A different equation of state would change how fast the universe grew at each era of its history, so the surveys measure the equation of state by measuring how fast the universe grew at each era. The surveys measure the growth in four ways: by the distances to exploding stars of a known brightness, by the spacing of galaxies, by the bending of light by matter, and by the pattern of the microwave background. Sound waves laid down the spacing of galaxies. The sound waves rang through the hot gas of the young universe and left a preferred distance between clumps of matter. Three coming instruments will map the history of the growth with far more galaxies and far more exploding stars than earlier surveys: the Euclid space telescope, the Vera C. Rubin Observatory and the Nancy Grace Roman Space Telescope. The Dark Energy Spectroscopic Instrument continues its survey, which maps galaxies to measure the history of the expansion.

Each measurement so far is given as its authors report it. The Planck satellite mapped the microwave background, and the Planck Collaboration is the team of the satellite. The Planck Collaboration combines the satellite's map with the spacing of galaxies and with exploding stars, and

the combined measurements give an equation of state of minus one and three hundredths, give or take three hundredths (Planck Collaboration 2020). In the final analysis of the Dark Energy Survey, the authors combine the survey's measurements with those of the Dark Energy Spectroscopic Instrument and the microwave background, and they fit an equation of state that changes as the universe grows (Abbott and others 2026). In the authors' fit, the present value of the equation of state is minus eighty-two hundredths, give or take five hundredths. A second fitted number is the rate at which the equation of state changes with the size of the universe, and the fitted rate is minus sixty-three hundredths, give or take about two tenths. The authors report the fit as three standard deviations from a constant equation of state. In the second data release of the Dark Energy Spectroscopic Instrument, the team reports a preference (DESI Collaboration 2025). The preference is for a present value of the equation of state above minus one, together with a dark energy whose density falls as the universe grows. The team states the preference as 3.1 standard deviations when its survey is combined with the microwave background, and as 2.8 to 4.2 standard deviations when exploding stars are added as well.

*The Gravitational Passage* is another book of this collection. *The Gravitational Passage* states what this account expects of the reports of the Dark Energy Survey and the Dark Energy Spectroscopic Instrument: "The account predicts that the reported departure will not be confirmed". "The reported departure" in that quotation means the departure from minus one that the Dark Energy Survey and the Dark Energy Spectroscopic Instrument report. The last section of this appendix states what "confirmed" means.

## Searches for the Decay of the Proton

The coming searches will measure how long a proton lasts. This account says that the searches will find the proton stable, at every lifetime that the searches can test.

In this account the forces form a product of three separate factors. The three factors are three separate symmetries: one for color (the charge of the strong force, which quarks carry), one for the weak charge (the label on which the weak force acts), and one for electric charge. Each carrier of force belongs to one of the three symmetries only, so no carrier of force joins color to the weak charge, at any energy. Protons and neutrons, counted together, change in number only when a quark turns into a particle without color. A quark carries color, so turning a quark into a particle without color would need a carrier of force that acts on color and on the weak charge at once, and there is no such carrier. So no process changes the number of protons and neutrons, counted together. The proton is the lightest particle made of three quarks, as measured (Chapter 5), so the proton has nothing lighter to become while keeping the count of protons and neutrons. Many theories that unite the forces predict that protons decay, because in them a carrier of force joins the quarks to the *leptons*, the electron and its kin.

In a search for the decay of the proton, a team watches an enormous number of protons for years, in a large tank deep underground. The team looks for the flash or the track of a proton breaking into lighter particles. One way for a proton to decay gives a positron (the electron's antiparticle) and a *neutral pion*. A neutral pion is a short-lived particle with no electric charge, made of a quark and an antiquark. Another way gives a *muon*, a heavier cousin of the electron, and a neutral pion. A third way gives a *kaon* and an *antineutrino*. A kaon is another short-lived particle of a quark and an antiquark. An antineutrino is the antiparticle of the neutrino. The neutrino is a particle with almost no mass and no electric charge that passes

through almost anything. The team counts one kind of decay at a time, and when the team sees no decay of one kind, the team sets a lower limit on the proton's lifetime for that kind of decay.

The coming instruments are Hyper-Kamiokande and the Deep Underground Neutrino Experiment. Hyper-Kamiokande is a water tank in Japan, far larger than Super-Kamiokande (Hyper-Kamiokande Proto-Collaboration 2018). Super-Kamiokande is an earlier and smaller tank in Japan, and the measurements of Super-Kamiokande come at the end of this section. If one of the Hyper-Kamiokande tanks sees no decay in ten years, the Hyper-Kamiokande team will set the proton's lifetime for the decay into a positron and a neutral pion above seventy-eight million billion billion billion years, at 90 percent confidence. On the same terms (one tank, ten years with no decay seen, 90 percent confidence), the team will set the lifetime for the decay into a kaon and an antineutrino above thirty-two million billion billion billion years. The Deep Underground Neutrino Experiment, DUNE, watches tanks of *liquid argon* (DUNE Collaboration 2020). Liquid argon is the argon of the air, cooled until the argon is liquid. DUNE's design report states the longest lifetime that DUNE can test in one exposure: four hundred thousand tonnes of argon, watched for a year. The same exposure can be made by watching a smaller mass of argon for longer. If DUNE sees no decay in the exposure of its design report, the DUNE team will set the lifetime for the decay into a kaon and an antineutrino above about thirteen million billion billion billion years. This account says that both instruments will find the proton stable.

The measurements so far come from the Super-Kamiokande detector in Japan, which has seen no proton decay (Takenaka and others 2020). The Super-Kamiokande team sets the proton's lifetime for the decay into a positron and a neutral pion above twenty-four million billion billion billion years. For the decay into a muon and a neutral pion, the team sets the lifetime above sixteen million billion billion billion years. Each of the two limits is at 90 percent confidence.

## The Lifetime of the Dark Matter

The coming measurements will measure how long the dark matter lasts. This account says that the measurements will find the dark matter stable at every lifetime that the measurements can test.

The dark matter is the subject of my book *The Weight of Possibility*, another book of this collection. The six small dimensions of possibility are six further directions that every point of space carries. The six small dimensions are curled up far smaller than the core of an atom (Chapter 4). A turn is the one end of the insides of all black holes, from which the next epoch begins. In this account the dark matter is a vibration of the six small dimensions of possibility. Each piece of the dark matter has about the Planck mass, the mass of the Planck scale, and each piece is made at a turn and kept until the next turn (*The Weight of Possibility*, Chapters 1 and 4). The dark matter has nothing to turn into: it cannot turn into ordinary matter, into waves of space and time, or into radiation of its own (*The Weight of Possibility*, Chapter 4, Sections II to IV), so the dark matter does not decay.

The stability of the dark matter sets this account's cycle of epochs apart from the cycle of the physicist Roger Penrose (Chapter 11). Penrose calls each whole history of the universe, from its big bang to its remote future, an aeon. In Penrose's conformal cyclic cosmology, the remote future of each aeon must be free of mass, so that the next aeon can join on to that remote future. Penrose calls his dark matter erebons. The erebons have mass, so the erebons must decay within each aeon. Penrose gives the erebons a lifetime of perhaps about a hundred billion years (Penrose 2018). So physicists can tell this account's cycle from Penrose's cycle by measuring the lifetime of the dark matter.

If dark matter decayed, matter would carry a falling share of the universe's energy over cosmic time, and so the universe would grow differently. A decay into particles that no detector sees would show in the his-

tory of the expansion and in the pattern of the microwave background, while a decay into light or into ordinary particles would show far more directly. Two kinds of coming measurement will measure the history of the expansion more closely. One kind comes from the coming maps of the microwave background, among them the Simons Observatory. The other kind comes from the coming surveys of galaxies, among them the Dark Energy Spectroscopic Instrument and Euclid.

The measurements so far come from the microwave background and the history of the expansion. For a decay of all of the dark matter into particles that no detector sees, the measurements bound the lifetime to beyond about a hundred and sixty billion years (Poulin, Serpico and Lesgourgues 2016). Penrose gives the erebons a lifetime shorter than the measured bound: perhaps about a hundred billion years (Penrose 2018), against a bound of about a hundred and sixty billion years.

## Primordial Gravitational Waves

The coming instruments will measure a twisting pattern in the polarization of the microwave background. The polarization of light is the direction in which the light vibrates. Gravitational waves are ripples in the shape of space and time itself. If gravitational waves were present from the beginning of our epoch, the waves would leave the twisting pattern in the polarization. Physicists call gravitational waves from the beginning of an epoch "primordial". This account says that the instruments will find that the first departures of the universe from uniformity were departures of density alone, with the twisting pattern far too faint to see.

Astronomers state the strength of primordial gravitational waves as a ratio. The ratio is the *power* of the waves, divided by the power of the first departures of density. The power of a pattern of ripples is the strength of the pattern, measured by the square of the ripples' size. In this account the first departures from uniformity are departures of density. The departures of density are carried across the turn as one form, the same for every

component of the content. Waves of space and time arise from the departures of density only at *second order*: as a side effect of the departures acting on one another, so that the strength of the waves goes as the square of the departures' small size. The square of a small size is far smaller still, so this account says that primordial gravitational waves have a power far below a millionth of the power of the departures of density (*The Gravitational Passage*, Chapter 18, Section XIII). The standard account of the early universe uses a brief burst of expansion, called inflation, and many models of inflation predict a ratio large enough for the coming instruments to find.

The coming instruments are the Simons Observatory and the LiteBIRD satellite. The Simons Observatory in Chile has a target uncertainty in the ratio of three parts in a thousand (Ade and others 2019). LiteBIRD, a planned satellite, is required to measure the ratio with an uncertainty below one part in a thousand (LiteBIRD Collaboration, Allys and others 2023). This account says that both instruments will find a ratio far below the smallest ratio that either instrument can detect. The instruments will find departures of density alone.

The measurements so far come from the BICEP and Keck telescopes at the South Pole. The BICEP and Keck telescopes map the polarization of the microwave background. The team of the BICEP and Keck telescopes combines its maps with those of the Planck and WMAP satellites, and the combined maps place the ratio below about three parts in a hundred, at 95 percent confidence (BICEP/Keck Collaboration 2021).

## The Flatness of Space

The coming surveys will measure the curvature of space on the largest scale. This account says that the surveys will find space flat.

Space on the largest scale could be curved like the surface of a ball, curved the other way like a saddle, or flat. Astronomers state the curvature as a share of a budget: the budget that sets how fast the universe grows. Matter takes one share of the budget, and the energy of

empty space takes another. The curvature share is the share that curvature would take beside the share of matter and the share of the energy of empty space. A flat space has a curvature share of zero.

The *smooth model* of an epoch is the picture of the epoch with every ripple smoothed away. In this account the smooth model of each epoch is flat. The beginning of an epoch holds no length carried over from the epoch before (Chapter 2). The only length that the beginning holds is the Planck length. The Planck length is the unit of length that the measured strength of gravity sets. Gravity and the quantum meet on equal terms at the Planck length. So the beginning could set a curvature only on the Planck length. Space curved on the Planck length would close up at once, or spread too fast for anything to gather. An epoch is an era in which stars, galaxies and black holes form, so the beginning of an epoch sets no curvature.

The actual space of our epoch is curved only by the epoch's own small departures from uniformity. The departures are about one part in a hundred thousand (*The Gravitational Passage*, Chapter 18, Sections IX and XIII). The curvature from the departures is far smaller than the smallest curvature that the coming surveys can detect, so, at the precision of the coming surveys, this account's statement is a curvature share of zero.

Two kinds of coming measurement will measure the curvature share more closely. One kind comes from the coming maps of the microwave background. The other kind comes from the coming surveys of galaxies, among them the Dark Energy Spectroscopic Instrument and Euclid. This account says the measured share will come ever closer to zero.

The measurements so far come from the Planck satellite, combined with the spacing of galaxies. The Planck Collaboration finds a curvature share of one part in a thousand, give or take two parts in a thousand (Planck Collaboration 2020). Zero lies inside the range of the uncertainty, so the measured share is zero within the measurement.

## How a Result Is Counted

This account fixes a rule in advance: the rule says when a measured result counts as settled. The rule is the same whether a result agrees with a prediction of this account or differs from the prediction. *The Gravitational Passage* states the rule: "confirmed means established at five standard deviations by at least two independent kinds of measurement". The rule requires a second, independent kind of measurement, so that an error in any one method cannot by itself make a result count as confirmed. When a difference between a measurement and a prediction is smaller than five standard deviations, the difference is a measurement of interest. I report a difference smaller than five standard deviations as a measurement of interest.

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# Key Concepts

Each entry below is a reminder of the explanation given at the place in the book where the term first appears, and each entry ends with the name of that place, in parentheses. In the entries, the words "this physics" mean the physics that I work out in my collection of books on physics.

**90 percent confidence.** Said of a limit that the result of a search would have crossed nine times in ten, if the true value lay beyond the limit. A limit stated at 95 percent confidence is a limit that the result of a search would have crossed nineteen times in twenty, if the true value lay beyond the limit (Appendix B).

**absolute zero.** The coldest any temperature can be: the temperature of a thing with no warmth to give at all (Chapter 1).

**aeon.** The physicist Roger Penrose's name for one whole history of the universe, running from a big bang to the remote future after that big bang (Chapter 11).

**afterglow.** The faint warmth left over from the Big Bang, which reaches us from every direction in the sky. Astronomers call the afterglow the microwave background (Chapter 1).

**AME.** Atomic Mass Evaluation: the published evaluation and tables of the measured masses of atoms. I cite the edition called AME 2020 (Appendix A).

**analog memory.** The physicist Freeman Dyson's name for a memory written in a smooth quantity, such as an angle, whose value can be read to more and more figures as the universe grows colder and quieter (Chapter 7).

**antineutrino.** The antiparticle of the neutrino. The neutrino is a particle with almost no mass and no electric charge, and a neutrino passes through almost anything (Appendix B).

**antiparticle.** The twin that every kind of particle has, with the opposite electric charge (Chapter 5).

**asymmetric.** Not staying the same. A diary is asymmetric, since every page of a diary differs from the page before, and nothing in the diary stays the same from page to page (Chapter 8).

**baby universe.** In the physicist Michio Kaku's plan of escape, a tiny region squeezed and heated until the region swells into a universe of its own, joined to our universe by a wormhole (Chapter 10).

**baryon.** A particle made of three quarks. Protons and neutrons are baryons (Chapter 5).

**baryon number.** The count of baryons in a body, with each antiparticle of a baryon counted as minus one (Chapter 5).

**BICEP.** Background Imaging of Cosmic Extragalactic Polarization: a series of telescopes at the South Pole. The BICEP telescopes and the Keck telescopes together map the polarization of the microwave background (Appendix A).

**Big Bang.** The hot, dense beginning that the history of our universe runs back to, as astronomers piece the history of our universe together (Chapter 1).

**biological scaling hypothesis.** An assumption that the physicist Freeman Dyson made about a copy of a living creature. Dyson assumed that when the copy runs on a smaller scale of energy, in surroundings colder by the same factor, the copy is alive and subjectively identical to the original creature. On Dyson's assumption, all the copy's vital functions are reduced in speed by the same factor. In plain words, a thinker built to run colder thinks the same thoughts as the original thinker, more slowly, and spends less energy on each thought (Chapter 7).

**black dwarf.** A white dwarf that has cooled until the white dwarf no longer glows: a dark, solid ball about the size of the Earth, still holding the mass of a star (Chapter 5).

**black hole.** A region in which matter is packed so densely that nothing can climb back out of the region, not even light. Physicists also call the boundary of a black hole a horizon (Chapter 1).

**bounce.** A contraction that turns into an expansion at a smallest size, as a dropped ball turns back upward at the floor (Chapter 11).

**bound.** Said of a body held together by the body's own gravity, or of an atom held together by the forces among the atom's particles (Chapter 3).

**brane.** A surface with three dimensions of space, like a sheet, set in a space with more dimensions. The word "brane" is short for "membrane" (Chapter 11).

**Chandrasekhar mass.** The greatest mass a white dwarf can have, about 1.4 times the mass of the Sun. Every white dwarf that astronomers have weighed lies below the Chandrasekhar mass (Chapter 5).

**COBE.** Cosmic Background Explorer: the satellite whose first year of maps showed that the microwave background is not perfectly even (Chapter 9).

**CODATA.** Committee on Data of the International Science Council. CODATA publishes the recommended values of the fundamental physical constants (Appendix A).

**color.** The charge of the strong force. Quarks carry color (Chapter 5).

**compare.** To set two things side by side and find whether the two things are the same or different (Chapter 1).

**comparer.** Anything that compares. The word "comparer" is this book's other name for an observer, and neither word means *only* a mind (Chapter 7).

**comparison.** The act of finding whether two things are the same or different, in some respect. Every observation, every measurement and every test is a comparison (Chapter 6).

**computation.** One rule applied the same way, step after step (Chapter 7).

**conformal.** Said of a change of scale that keeps the shapes of things, every angle and every path of light, while letting every size change, as a map redrawn at a larger scale keeps every angle of every coastline (Chapter 11).

**consciousness.** In this book, three features of an act of comparison, taken whole, in a context, as one act happening. The three features are these: the comparison runs one way, from the comparing to the record the comparison leaves; the outcome of the comparison is something that nothing before the comparison fixed; and the comparison is made from a stance. When you hear a note of music, the hearing holds the three features together as one act: the note (the one-way order), the surprise (the outcome that nothing fixed) and the listener (the stance) (Chapter 7).

**content.** What a comparison finds. When a thermometer is read this morning and again this evening, the content is the temperature, warmer in the evening than in the morning (Chapter 6).

**context.** The respect in which a comparison finds its content: the setting that makes the two things compared two. For a thermometer read in the morning and in the evening, the two times of day are the context (Chapter 6).

**continuous.** Without a break. A ramp is continuous, since a ramp rises with no sudden step anywhere (Chapter 8).

**cosmic strings.** In the physicist Michio Kaku's account, thin threads of concentrated energy that the early universe may have left stretched across space. Cosmic strings are a different thing from the tiny strings of string theory (Chapter 10).

**cosmological constant.** The simplest form that dark energy can take. Astronomers define the cosmological constant as an energy of empty space itself. The cosmological constant is the same amount of energy in every cubic meter of space, everywhere, and at every time in the history of our universe: the cosmological constant does not thin out as space grows (Chapter 1).

**cosmological event horizon.** The boundary beyond which no event can ever send a signal to a given observer. Each observer has a cosmological event horizon of its own, centered on the observer. In this book I usually call the cosmological event horizon simply the horizon (Chapter 1).

**cosmology.** The science of the universe as a whole (Chapter 1).

**CPT.** Charge conjugation, parity and time reversal: the three changes, taken together, that the CPT theorem concerns (Appendix A).

**curvature.** The way space as a whole can be bent. A curvature radius says how far you would have to travel before the bending showed, as the size of a ball says how far you must walk on the ball before you come round to where you started (Chapter 2).

**dark energy.** Whatever drives the speeding up of the expansion of the universe. The name has a reason for each of its two words: "dark", because dark energy gives off no light, and "energy", because dark energy acts on the expansion as an energy does (Chapter 1).

**dark matter.** The unseen matter whose pull astronomers measure in every galaxy (Chapter 5).

**de Sitter universe.** A universe whose expansion is driven by a cosmological constant (Chapter 7).

**decay.** Of a particle: to break up into lighter particles (Chapter 5).

**degeneracy pressure.** The pressure that a crowd of electrons exerts because, by exclusion (the rule that no two electrons can be in the same state), the electrons cannot all settle into the lowest states. Degeneracy pressure needs no heat at all (Chapter 5).

**density.** The amount of matter and energy packed, on average, into each cubic meter of space (Chapter 2).

**departures from uniformity.** The faint differences of density with which an epoch begins. The galaxies of the epoch later grow from the faint differences, by gravity (Chapter 9).

**DESI.** Dark Energy Spectroscopic Instrument: a survey that maps galaxies in order to measure the history of the expansion (Appendix B).

**discontinuous.** In separate steps. A staircase is discontinuous, since a staircase rises in separate steps (Chapter 8).

**dissipate.** Of energy that can do work: to spread the energy out as heat, in a form from which no more work can be drawn (Chapter 8).

**domain.** A whole world within which comparisons can be made (Chapter 10).

**DUNE.** Deep Underground Neutrino Experiment: a set of tanks of liquid argon, built to search, among other aims, for the decay of the proton (Appendix B).

**electron.** One of the particles that circle the nucleus of an atom, much lighter than the protons and neutrons of the nucleus (Chapter 3).

**energy density.** The energy in each cubic meter (Appendix B).

**entropy.** A count of the arrangements of a thing's parts that leave the thing looking the same from outside. Chapter 8 adds that every count of arrangements is made against a context (Chapter 7).

**epoch.** One era of the world, in which stars, galaxies and black holes form. Our own epoch is the era whose history runs back to the Big Bang (Chapter 1).

**equation of state.** The rule that ties a substance's pressure to the substance's density. For the stuff of the universe, the equation of state is one number: the pressure divided by the density (Chapter 3).

**evaporation.** The slow loss by which a black hole shrinks by its own faint glow until, in the end, nothing of the black hole is left (Chapter 5).

**exclusion.** The rule that no two electrons can be in the same state: no two electrons can share both the same place and the same motion (Chapter 5).

**expansion.** The growth with time of the distances between galaxies that are not held together by gravity. The distances grow because space itself is stretching (Chapter 1).

**expansion rate.** How fast a galaxy recedes for each unit of the galaxy's distance from us. At a given time the expansion rate is the same for every galaxy, and the expansion rate says how fast the universe as a whole is growing (Chapter 1).

**false vacuum.** A settled state of empty space that holds for now but is not the lowest state that empty space could have (Chapter 4).

**field.** A quantity with a value at every point of space, as temperature has a value at every point of a room (Chapter 2).

**finding.** What one act of comparison yields: one outcome, laid down as a record (Chapter 7).

**flat.** Said of space that is bent neither one way nor the other, so that lines that start out side by side stay side by side for ever, as in the geometry taught at school (Chapter 2).

**form of the content.** What the matter is, and which alternatives the matter has taken. The word "information" has two senses in physics, and the form of the content is information in the first sense. The form of the content is carried with the matter wherever the matter goes (Chapter 9).

**forms of matter.** The forms that matter takes in our epoch, such as atoms, molecules, cells, stars and bodies. The held shape of the six small dimensions fixes the forms of matter (Chapter 7).

**galaxy.** An island of a hundred billion stars or more, held together by its own gravity, with wide dark gulfs between the island and the next islands. The disc of the Milky Way is our own galaxy (Chapter 1).

**GeV.** Giga-electronvolt: one billion electronvolts, a unit of energy used in particle physics (Appendix A).

**grand unified theories.** Theories that join three forces into one: the strong force, the weak force and the electric force (Chapter 5).

**gravitational waves.** The ripples in space that moving masses send out (Chapter 11).

**heat death.** A final state in which everything has one temperature, the entropy of everything has reached its largest value, and nothing ever happens again (Chapter 8).

**hibernation.** In the physicist Freeman Dyson's sense, thinking in bursts. A society that hibernates thinks for a short stretch and then sleeps, and while the society sleeps, the society uses almost no energy and keeps radiating away the heat of its last burst of thinking (Chapter 7).

**Higgs boson.** A small ripple of the Higgs field (Chapter 4).

**Higgs field.** A field that fills all of space and has settled at a value that is not zero, the same everywhere. Many of the elementary particles get their masses from the settled value of the Higgs field (Chapter 4).

**horizon.** Short for cosmological event horizon: the boundary beyond which no event can ever send a signal to a given observer. Physicists also call the boundary of a black hole a horizon: the surface from inside which no signal can reach the outside. Where a reader could doubt which horizon is meant, this book says "the black hole's horizon" or "the cosmological horizon" (Chapter 1).

**Incommensuration Theorem.** A structural fact about the nature of knowing. The Incommensuration Theorem states that, at the foundation of any comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity (Chapter 8).

**information.** A word that physics uses in two senses. I keep the two senses apart. In the first sense, information is the form of the content: what the matter is, and which alternatives the matter has taken. In the second sense, information is a count of states relative to a context (Chapter 9).

**inside.** A side that is a thing's own, from which the comparing is done and to which the outcome happens. When a thing has the three features of consciousness together, this book says that the thing has an inside. The entry for "consciousness" lists the three features (Chapter 7).

**internal space.** Another name for the six small dimensions (Chapter 4).

**kaon.** A short-lived particle made of a quark and an antiquark (Appendix B).

**landscape.** In string theory, the whole set of the states into which empty space could settle, pictured as a many-valleyed country, with each valley having its own energy of empty space and its own physics (Chapter 4).

**lepton.** A member of the family of light particles to which the electron belongs (Chapter 5).

**LIGO.** Laser Interferometer Gravitational-Wave Observatory: the detectors that first recorded the gravitational waves of two merging black holes (Appendix A).

**linear relation.** The simplest kind of relation there is: twice as far, twice as fast. Among the galaxies, a galaxy twice as far away from us recedes twice as fast (Chapter 1).

**liquid argon.** The argon of the air, cooled until the argon is liquid (Appendix B).

**LiteBIRD.** Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection: a planned satellite that is to measure the polarization of the microwave background (Appendix B).

**Local Group.** The small family of galaxies, bound together by gravity, to which our galaxy belongs: our galaxy, Andromeda, and some dozens of smaller galaxies (Chapter 1).

**massless particle.** A particle that weighs nothing even when still, such as the photons that make up light and the gravitons that make up gravitational waves (Chapter 11).

**mechanics.** The science of motion (Chapter 6).

**metastable.** Said of a state that is held, and could pass by tunneling to a lower state, but lasts far beyond the age of the universe (Chapter 4).

**MeV.** Mega-electronvolt: one million electronvolts, a unit of energy used in nuclear and particle physics (Appendix A).

**microwave background.** The afterglow of the Big Bang. Astronomers call the afterglow the microwave background because the expansion has stretched the afterglow's light into microwaves, waves far longer than the waves our eyes can see. The microwave background is the oldest light that reaches us (Chapter 1).

**momentum.** The amount of motion (Chapter 2).

**MS-bar.** Modified minimal subtraction: a standard rule by which physicists fix how a coupling, such as the self-coupling of the Higgs field, is defined at a given energy (Appendix A).

**muon.** A heavier cousin of the electron (Appendix B).

**negative energy.** A state of a field with less energy than empty space (Chapter 10).

**neutral pion.** A short-lived particle with no electric charge, made of a quark and an antiquark (Appendix B).

**neutron.** One of the two sorts of particle of which the nucleus of an atom is made: the sort that carries no electric charge (Chapter 3).

**neutron star.** A ball more massive than the Sun and some twenty-five kilometers across, packed as tightly as the nucleus of an atom and made mostly of neutrons. A star much heavier than the Sun leaves a neutron star when the star ends (Chapter 5).

**no-hair theorem.** A standard theorem of gravity: once a black hole has settled, all that can be registered of the black hole from outside is the black hole's mass, electric charge and spin (Chapter 8).

**observer.** Anything that compares one thing with another and registers the result: you on your back step looking up at the night sky, an astronomer at a telescope, a camera, a photographic plate. Being an observer is a role that anything inside the world can fill, and filling the role does not need a mind (Chapter 1).

**ORCID.** Open Researcher and Contributor ID: a number that identifies an author of research. My ORCID is printed on the copyright page of this book (copyright page).

**outside world.** The whole of what can ever reach an observer and be set beside the rest of what the observer receives: every star, galaxy and glow whose light or signal arrives at the observer, now or later (Chapter 1).

**phantom energy.** The physicist Robert Caldwell's phantom: a substance whose equation of state is below minus one, so that the substance grows denser as space expands (Chapter 3).

**photon.** A single particle of light (Chapter 7).

**Planck length.** The length of the Planck scale, far smaller than an atom (Chapter 2).

**Planck scale.** The scale of length, time and energy at which gravity and the quantum meet on equal terms, so that neither gravity nor the quantum can be left out. At the Planck scale two descriptions of the

world reach their edge, the limit past which each description no longer holds: the smooth description of gravity and the quantum description (Chapter 2).

**power.** The strength of a pattern of ripples, measured by the square of the ripples' size (Appendix B).

**pressure.** The push on each small piece of a surface, as the air inside a balloon pushes outward on every square inch of the rubber (Chapter 3).

**proton.** One of the two sorts of particle of which the nucleus of an atom is made: the sort that carries a positive electric charge. The nucleus of the simplest atom, hydrogen, is a single proton (Chapter 3).

**pycnonuclear fusion.** The astrophysicist Matt Caplan's name for fusion of nuclei pressed together by the density of a star (Chapter 5).

**quantum.** The physics of the very small (Chapter 2).

**quantum description.** The physics of the very small, in which matter comes in separate steps. At the Planck scale two descriptions of the world reach the limit past which each description no longer holds: the quantum description and the smooth description of gravity (Chapter 2).

**quark.** One of the smaller particles of which protons and neutrons are each made, three to each (Chapter 4).

**radiation.** Light and other rays that carry energy away (Chapter 1).

**real.** In this physics, given in an actual act of comparison, here and now (Chapter 7).

**recollapse.** The expansion of the universe as a whole stopping, turning around, and contracting all of space together (Chapter 2).

**redshift.** The stretching of light into longer, redder waves on the light's way to us (Chapter 1).

**rest mass.** The mass a body has when the body is still (Chapter 11).

**rotation against the distant stars.** The standard of turning and of stillness: to be still or to turn is to be still or to turn relative to the matter far away, and the matter far away fixes what counts as not rotating (Chapter 6).

**second order.** Said of an effect that arises only as a side effect of small departures acting on one another, so that the strength of the effect goes as the square of the departures' small size (Appendix B).

**singularity.** The place where the smooth description of space and time reaches the edge of the range in which the smooth description holds (Chapter 9).

**six small dimensions.** Six further directions that every point of space carries, besides the three directions of space and the one direction of time. The six small dimensions are curled up far smaller than the core of an atom, to about the size of the Planck length. Physicists also call the six small dimensions the internal space. The six small dimensions are held in their shape, and the held shape fixes the forms that matter can take (Chapter 4).

**smooth description of gravity.** Einstein's theory of gravity, which treats space and time as smooth. At the Planck scale two descriptions of the world reach the limit past which each description no longer holds: the smooth description of gravity and the quantum description (Chapter 2).

**smooth model.** The picture of an epoch with every ripple smoothed away (Appendix B).

**stance.** The side from which a comparison is made, facing something to be compared (Chapter 6).

**standard deviation.** The usual measure of how far a measurement might wander from the true value by chance. Chance would give a result five standard deviations away from the true value less than once in a million tries (Appendix B).

**Standard Model.** The established account in physics of the particles, and of every force except gravity (Chapter 4).

**states.** Of empty space, in string theory: the many different conditions into which empty space could settle, as a ball can come to rest in any one of many valleys (Chapter 2).

**string theory.** A proposed theory in which the smallest pieces of matter are tiny vibrating strings (Chapter 2).

**strong force.** The force that binds quarks together (Chapter 5).

**subjective time.** Time as a creature itself lives it. In the physicist Freeman Dyson's scheme, subjective time runs more slowly as the creature runs colder (Chapter 7).

**superheated liquid.** A liquid heated past its boiling point and kept from boiling (Chapter 4).

**supernova.** A star that blows itself apart. For a few weeks a supernova can shine as brightly as a whole galaxy (Chapter 1).

**symmetric.** Staying the same through a change. A law that holds in every city is symmetric, since the law stays the same through the change from one city to another (Chapter 8).

**tension.** A negative pressure: a pull, as a rubber band stretched between your hands pulls inward on your hands (Chapter 3).

**third axiom.** The third of three axioms in which this physics states the structure of every comparison. The third axiom states that content and context are distinct and inseparable: there is no content without a context in which the content is content, and no context without a content (Chapter 8).

**throat.** The narrowest part of a wormhole (Chapter 10).

**true vacuum.** In the picture of a ball among valleys, the bottom of the lowest valley of all: the lowest settled state of empty space (Chapter 4).

**tunneling.** The passing of a ball held in a valley through the ridge into a lower valley, without the ball ever climbing over the top of the ridge. In the picture of a ball among valleys, the ball is empty space and the valleys are the settled states of empty space. Quantum physics allows tunneling (Chapter 4).

**turn.** The one end of the interiors of all black holes: the interiors of all black holes end in one and the same end. The turn is a limit, approached from the side of the old epoch and from the side of the next epoch, and reached from neither side. The turn is *not* an event that a history goes through. The next epoch begins from the turn (Chapter 4).

**uncertainty.** Of a measurement: the range within which the true value most likely lies. The uncertainty is written $\pm$ and read "give or take" (Appendix B).

**vacuum.** The settled state of empty space: what empty space is like when nothing at all is put into it (Chapter 4).

**warp drive.** A ship that would shrink the space ahead of the ship and stretch the space behind the ship (Chapter 10).

**weak charge.** The label on which the weak force acts (Chapter 5).

**weak force.** The force at work in some kinds of radioactive decay (Chapter 4).

**white dwarf.** The cooling remnant of a star that has burned its fuel, about as heavy as the Sun and about as large as the Earth. A star like the Sun leaves a white dwarf (Chapter 5).

**white hole.** The time reverse of a black hole: a white hole would throw out what a black hole takes in (Chapter 10).

**WMAP.** Wilkinson Microwave Anisotropy Probe: a satellite that mapped the microwave background (Appendix B).

**wormhole.** A shape of space and time, allowed by Einstein's equations, in which a short passage joins two places that are otherwise far apart (Chapter 10).

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