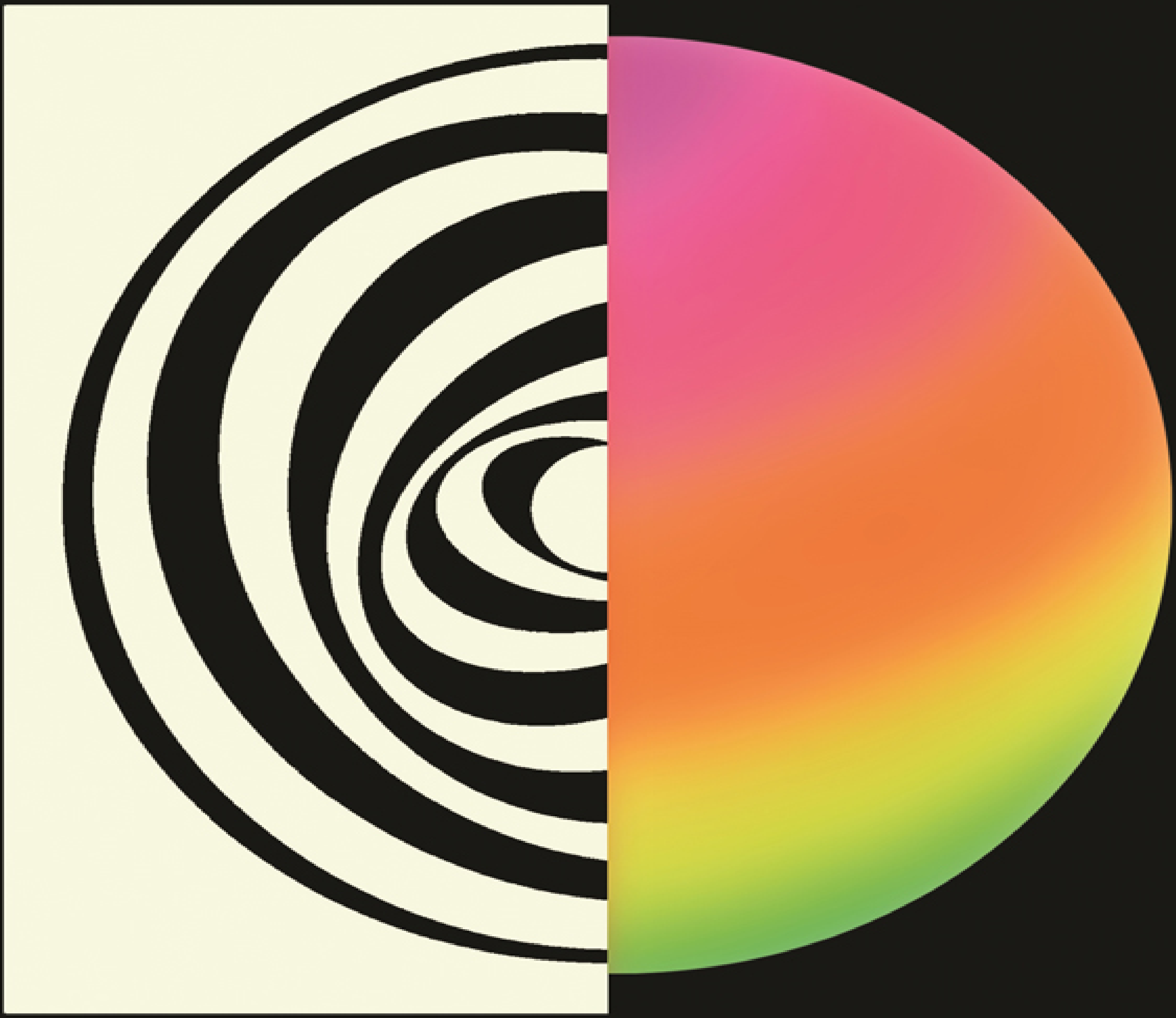
The Edge of Space-Time

Particles, Poetry and the Cosmic Dream Boogie



'With this extraordinary book, Prescod-Weinstein cements her status as one of the most accomplished and important science writers of our time' **ED YONG**

Chanda Prescod-Weinstein

The Edge of Space-Time

Also by Chanda Prescod-Weinstein

The Disordered Cosmos: A Journey into Dark Matter,
Spacetime & Dreams Deferred

The Edge of Space-Time

Particles, Poetry and the Cosmic Dream Boogie

Chanda Prescod-Weinstein

CANONGATE

First published in Great Britain in 2026
by Canongate Books Ltd, 14 High Street, Edinburgh EH1 1TE

canongate.co.uk

First published in the USA in 2026 by Pantheon Books, a division of
Penguin Random House LLC, 1745 Broadway, New York, NY 10019

This digital edition first published in 2026 by Canongate Books

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British Library Cataloguing-in-Publication Data
A catalogue record for this book is available on

request from the British Library

ISBN 978 1 83726 104 8
eISBN 978 1 83726 106 2

The manufacturer's authorised representative in the EU for product safety is BGC Sustainability & Compliance, 7 avenue du Général Leclerc, Paris 75014
(gpsr@baldwinglobalconsulting.com)

For Grandpa Norman ז״ל

For Karsten Pohl ז״ל

For my dad, Sam Weinstein, who gifted me the world
of poetry and read Alice *aloud with me*

For my uncle, Peter Prescod, who gave me my
first copy of A Brief History of Time

For all the freedom dreamers who stay curious

Space. The final frontier. Above us. Around us. Within us. We have always looked to the stars to discover who we are. A thousand centuries ago in Africa, the |Xam Abathwa tribe gathered to share a story. The tale of a girl who dug her hands in the wood ash and threw it into the sky to create the Milky Way. And hidden there, a secret buried among the eternal stars, was a message. An enormous letter in a bottle made of space and time, visible only to those whose hearts were open enough to receive it.

—Sonequa Martin-Green as Michael Burnham,
Star Trek: Discovery, Season 2, Episode 1

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IV. Let's Fly

SANKOFA!

sɛ wo werɛ fi na wosan kƆfa a, yɛnkyi
it is not incorrect to go back and get what you forgot

—Akan proverb

We are called to go back and get the history of space-time. And who am I to argue with the ancestors?

Even so, I do. *Science in this society is often done for the wrong reasons,* I find myself telling them. And they remind me that because it's my job to study the origin and evolution of the universe and everything inside it, *I* know there is a location in space-time where the universe became transparent to light, the first place where light could fly free. The ancestors, who by all accounts were quite curious about star stuff, insist: This is a story that I have learned so I could tell it to others. To do cosmology—to study the beginning and evolution of space, time, and matter—is to be a griot, a keeper of stories and history. To do cosmology is to go back and get the beginning, to map out the future.

So: Quite nearly at the beginning, the universe said let there be light. And particles of light—photons—all of them traveling at the speed of light, the fastest in the universe, couldn't get very far. They were stuck in a plasma stew where they constantly bumped into particles, especially electrons, which swallowed their energy and spat it out in the form of new photons and other particles.

Humanity has only been aware of this cosmic light for sixty-two years. It has been there almost since the beginning of everything and has been traveling for nearly 14 billion years. It was there when the universe was cool enough for atoms to form. It was with the sun when it was just a cloud of gas, and it was there when the sun's hydrogen ignited with fusion, turning the sun into a star. It was there when the leftovers from the gas cloud condensed into planet Earth. And it was there when carbon-based life-forms evolved into apes.

This light is a cosmic edge: We cannot look directly past it because at any time earlier than that, the photons were trapped, unable to get out. And this edge is a reminder that physics is a way of gaining deep insight into the universe, one we can add to the variety of overlapping forms of knowing that we have long used. To understand this boundary, and how we have come to know about it, is to deepen our relationship with ourselves and the universe around us in a very specific and beautiful way. We should embrace it, for ourselves, and for future generations, because it is our history—and who are we to argue with the ancestors?

• • •

The book you are reading is about the queer, poetic wonder that is our universe and what we gain when we look at it from the margins. It is my version of what historian Aimé Dafon Sègla calls cosmovisions, a response to the question of why we should bother trying to get beyond the edges of human knowledge about the physical universe.[1] *The Edge of Space-Time* is part of a larger tradition that includes not just scientists but also artists. People like jazz musician, artist, and technologist Milford Graves, who used percussion, sound, and observations of praying mantises and plant growth to understand a phenomenon he termed "cosmic energy." Graves was not formally trained as a scientist, and "cosmic energy" sounds a little like mystic talk. But when I listened to him describe his ideas in the documentary *Milford Graves Full Mantis,* I heard a familiar sensibility about how matter is linked with and through space-time, a relationship that takes center stage in this book.

As a set of knowledges and techniques, physics provides a pathway toward answering the same questions Graves asked about the fundamental nature of our cosmos and the relationship between matter, energy, and space-time. It allows us to specify in great detail the relationship between photons and the plants in Graves's garden which transformed the photons into living particles. It is another entry point to what plant biologist and Black feminist theorist of intersectionality in science Beronda L. Montgomery calls lessons from plants.[*]

When it's at its best, physics is a kind of poetry, a story about the cosmos that is made from metaphors—and a producer of metaphors in its own right. I believe that seeing the universe through the perspective offered by physics strengthens our ability to understand what work metaphors are doing on us and how we might wield them. It is in this sense that physics works on us like poetry: a way of understanding the world that provides insights not available to us elsewhere.

This helps us see why we should bother with it. We should bother with physics because it is, in part, how we as a species learn to use our minds. We should learn and teach poetry, physics, algebra, and other abstract ideas because they train us to think in symbolic and figurative terms. The same goes for calculus and quantum mechanics. And if we cannot learn to think in and through the abstract and the symbolic, then we are pliable. We are sitting ducks for the fascists and authoritarians who will use us for their ends, and their ends are ultimately catastrophe for the rest of us. That's always been true, and it always will be.

In a world where genocides (plural) can be live-streamed and still continue unabated, it is hard to imagine that society could be otherwise when what is broken about it feels so total and, in the case of the families shattered and lives lost, so final. I don't think cosmology by itself can save the world. Even so, I believe in the ways that people experience a connection to the cosmos as nourishing. And I believe in preparing for the better world that is coming.

The 1951 book-length poem *Montage of a Dream Deferred* by Langston Hughes opens with a scene—"Dream Boogie"—centered on Black brilliance, Black struggle, and Black defiance:

> Good morning, daddy!
> Ain't you heard
> The boogie-woogie rumble

Of a dream deferred?[2]

Those of us living through these times of genocide and global warming know intimately the meaning of the phrase "dream deferred." Hughes wrote from a time of extreme repression of Black people, especially those whose sexuality, like his, refused confinement in heterosexuality. Sadly, his words have continued to speak to generations of Black/queer folks—including my own and the ones coming up after us. Even so, like Hughes, I write with the belief in the sound of the boogie-woogie rumble—the grief of the blues, yes, but also the brilliance of the blues. There is power in these sounds of defiance, in the communities that make them, and the dreams we stubbornly dream anyway. *The Edge of Space-Time* is about the ways in which our relationship to the cosmos can be part of our boogie-woogie rumble: our challenge to a dream deferred.

The past often gives us difficulty, but it is also what makes us. Sankofa, the concept underlying the Akan proverb I began with, means the past is a foundation and guide for the future. As a child, I learned to understand the past on these terms from Ethiopian director Haile Gerima's 1993 film *Sankofa*. I saw it around the same time that I first saw Errol Morris's documentary *A Brief History of Time,* which inspired me to pursue the life of a theoretical physicist. In Gerima's film, a griot (community storyteller) shouts "Sankofa!" repeatedly at the lead character—bidding her to listen for the stories of her kidnapped and enslaved African ancestors. To move forward and be her true, liberated self, she must be willing to confront the past.

And there is more to the past than horror. Cosmic history is Black history. As Afrocentric poet Listervelt Middleton wrote in "On the Origins of Things": "look around you Black child / your creation is everywhere."[3] To show ourselves and the world who we are means to understand that we too are a cosmic manifestation. Reflecting on how to translate the concept of Sankofa into English, G. F. Kojo Arthur writes in *Cloth as Metaphor: (Re)reading the Adinkra Cloth Symbols of the Akan of Ghana,* "There is nothing wrong with learning from hindsight . . . The word 'SankƆfa' is derived from the words SAN (return), KƆ (go), FA (look, seek and take). This symbolizes the Akan's quest for knowledge with the implication that the quest is based on critical examination, and intelligent and patient investigation."[4] Not only is there nothing wrong with learning, there is also nothing wrong with having questions that are not readily answered. Physics is a practice of struggling to get answers—and always finding new questions among them. It is a kind of dreaming, of universes that may be, in order to understand the universe that certainly is.

Dreaming isn't always easy, especially when catastrophe feels so imminent. I think of Wasim Said, the Gazan physics student who has been forced to put his dreams on hold while he struggles to stay alive in the midst of genocide.[5] In these conditions, I find myself wondering: What happens when our young people feel that they no longer have room to dream of something bigger than mere survival? To experience the sacred connection many people feel when they get to look at a dark night sky? I believe this is how we risk losing our humanity. Every work of dystopian fiction makes this clear to us.

Facing the imminent spiritual and perhaps physical destruction of our species can feel overwhelming, but we must prepare ourselves to face down the threat. As Egyptian American sociologist Heba Gowayed texted me on a particularly difficult day: "We cannot let the violence define meaning." Even Octavia Butler's prescient *Parable* series, which accurately forecasted the horrific 2025 Los Angeles County fires almost to the day, as well as the rise of Donald Trump, offered us a vision of humans in terrible conditions, stubbornly holding on to that which makes them human. Lauren Olamina's community in *Parable of the Sower* defiantly maintains knowledge of their circumscribed natural world. This is a teaching: There is another way of being in science that is independent of imperialist, nationalist, and white-supremacist systems.

Now, more than ever, we are forced to reckon with the fact that science is political. We must make a choice about who we will be, whether we will do science, and what ends our science will serve. I believe we should stay curious and do science because our humanity requires it, but this means we must also do science in a way that respects one another's humanity. This kind of intellectual work, which for the researcher comes primarily from a place of curiosity and desire to know the world, is a lot like the arts. Like paintings. Like sculpture. Like poetry.

The philosophy of *The Edge of Space-Time* is that in order to move forward, we must always reach back to our past and use it as a motivation and a guide. Human history is a matter of cosmic evolution, not just biology. Asking hard questions about the universe helps us get comfortable with being someone who asks hard questions, especially of those who want our votes, money, and labor in return.

* * *

Sankofa! Go back and get your cosmic dreams. It is how we create ourselves and our futures. Anton Hur's speculative novel *Toward Eternity* notes: "Poets are artists who write selves into being."[6] Scientific storytelling is also part of how we write ourselves into being. As with poetry, we do so through symbol and metaphor. I urge you to embrace a lesson from Beninese philosopher Paulin Jidenu Hountondji: "The realm of the thinkable is immense."[7] Know that the realm of the thinkable is *our* realm. My mom (Margaret Prescod) was right when she told me that it is our task to know something about this place that is bigger than the bad things that are happening to us. We have the opportunity to find joy in this incredible universe, joy that can sustain us through difficult times and motivate us to make better ones.

My own wish is for you to experience the cosmos through a cosmologist's eyes, if only for a little while. Physics is exciting—and it is also challenging. Math isn't the main challenge, either. That part anyone can learn (yes, you!), given the right resources and time. What makes physics hard is that you must be willing to change your worldview when the math, the experiments, and even sometimes theories demand it. You must be willing, like Alice in Wonderland, to go through the looking glass, again and again. And there is an incredible reward on the other end. Once you learn to approach the world through the looking glass of physics, you have gained access to a point of view that will always be available to you.

In Part I, "The People Could Fly," we'll dive deep into the standing question of what space is and meet the theories of motion and light along the way. In Part II, "Queer Phenomenology," you'll read stories about particles that spin without spinning and the conceptual challenge of trying to establish the past for even a single electron. In Part III, you'll go "Through the Looking Glass" and meet the universe on its most fundamental terms, where particles are a strange emergent phenomenon, space-time is getting away from itself, and black-hole science is easy. Finally, in Part IV, "Let's Fly," you'll be asked to think about big-picture questions of matter and meaning in a moment of great peril for our planetary ecosystems.

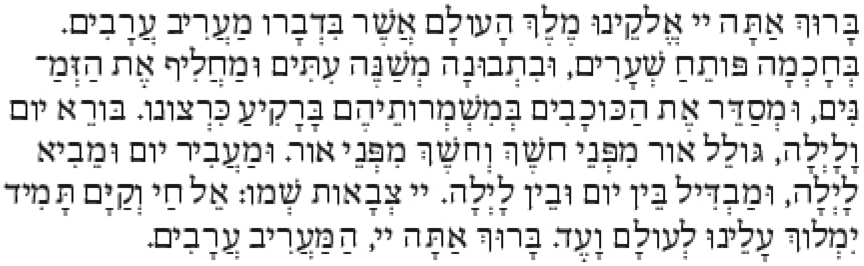
Imagine turning on a light and experiencing the wonder of knowing that doing so has produced a cascade of particles that have emerged from nothing and whose fundamental nature shook the foundations of physics. This knowledge created a new sensation in me that has softened with time but never fully dissipated. When you know a little about the abstract nature of the universe, it looks and feels different from before—and no one can take that experience away from you. This way of being in conversation with the cosmos isn't just for physicists. You too can have your mind altered—no drugs necessary.

The universe is too fucking fabulous for capitalism, y'all. Don't let it mediate your relationship with the cosmos, which is literally a boogie wonderland (to borrow a phrase from Earth, Wind & Fire). What happens when we don't let the military-industrial complex facilitate our rational investigations into how our universe works? Let's run the experiment. Be curious. Stand on the edge of space-time and look at the universe through the lens of non-trinary neutrinos, the multiverse, and wave-particle duality. And remember: Capitalism is temporary. The rest of the universe will still be there when capitalism is long gone. It's not gone yet, of course, and challenges lie ahead. But we are not required to commit every moment to our misery. As my mom told me while I was working on this book and worrying over whether anyone would be excited about the glories of the cosmos, "Without joy, what the fuck is the point?"

And on that note, let me offer some advice about how to read this book. This is supposed to be fun, and there is no test at the end. Please enjoy yourself. If you forget the definition of an idea I've described, use the index to find where the idea was first explained. Draw as it strikes your fancy and make a note about what sparks your interest. Don't be intimidated by the length, either. To reach the most elaborate heights abstraction takes us to requires a careful build. Concepts you meet in Part I have the potential to surprise you in Parts III and IV, especially when put in conversation with ideas in Part II.

• • •

Octavia Butler, who knew that she would have to fight to succeed as a Black woman writing speculative fiction, once told herself: “So be it! See to it!”[8] *So nu,* as my Grandpa Norman Weinstein **ז״ל** might have said in his childhood language of Yiddish, *der kosmos iz*. Let’s see to this incredible experience, the cosmic dream boogie.



בָּרוּךְ אַתָּה יי אֱלֹקֵינוּ מֶלֶךְ הָעוֹלָם אֲשֶׁר בִּדְבָרוֹ מַעֲרִיב עֲרָבִים.
בְּחָכְמָה פּוֹתֵחַ שְׁעָרִים, וּבִתְבוּנָה מְשַׁנֶּה עִתִּים וּמַחֲלִיף אֶת הַזְּמַ־
נִּים, וּמְסַדֵּר אֶת הַכּוֹכָבִים בְּמִשְׁמְרוֹתֵיהֶם בָּרָקִיעַ כִּרְצוֹנוֹ. בּוֹרֵא יוֹם
וָלָיְלָה, גּוֹלֵל אוֹר מִפְּנֵי חשֶׁךְ וְחשֶׁךְ מִפְּנֵי אוֹר. וּמַעֲבִיר יוֹם וּמֵבִיא
לָיְלָה, וּמַבְדִּיל בֵּין יוֹם וּבֵין לָיְלָה. יי צְבָאוֹת שְׁמוֹ: אֵל חַי וְקַיָּם תָּמִיד
יִמְלוֹךְ עָלֵינוּ לְעוֹלָם וָעֶד. בָּרוּךְ אַתָּה יי, הַמַּעֲרִיב עֲרָבִים.

> *Blessed are You, Universe, who brings in the evening with a word, in wisdom opening the gates and with understanding changing the times and seasons, ordering the stars along their paths in the sky. Creator of day and night, rolling back light from the dark and dark from the light, You make the day slowly fade and bring in the night, dividing between day and night, how great is Your Name. Living Universe, may we always feel your Presence in our lives. Blessed are You, Adonai, who brings in the evening.*

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* This is also the title of a beautiful book by Dr. Montgomery.
Go to note reference *

I.

THE PEOPLE COULD FLY

CHAPTER ONE

HOW TO LIVE SAFELY IN A SCIENCE FACTUAL UNIVERSE

In which we notice that we need metaphors to live (and do science)

Before the lab, before the data collection, there is language. Language is sometimes direct and quite literal: "The prettiest rose is a red rose." But it is just as often figurative, working through comparisons that require imagination to comprehend them. To tell you the story of space-time is to use figurative language, most especially the metaphors that so many of us use to understand our everyday lives. Think about how the idea of space-time as a "fabric" has become culturally ubiquitous. Meanwhile, physicists describe electricity and magnetism as "fields." What does it mean to explain abstract ideas by drawing on these comparisons to our lived environments and everyday objects?

It would be easy to jump into the science and the metaphors without spending time thinking about what exactly we are doing when we do so. But if we are to think carefully about the fundamental nature of the universe and everything inside of it—from space-time to the invisible dark matter that we've never seen or touched but feel fairly confident makes up most of the matter in the universe—then that means thinking carefully about metaphors and what work they are doing in our lives and scientific habits. As a physicist and science communicator, I live with the weight of the metaphors we choose in science, asking myself almost daily: "Is this the right one? What misunderstandings does this metaphor induce?" I ask these critical questions while also knowing that I am completely dependent on metaphors for my own understanding.

We live and breathe the world through metaphor, and our earliest metaphors have the power to govern our thinking. These are the lessons that Natasha Trethewey offers us in her 2020 essay, "You Are Not Safe in Science; You Are Not Safe in History: On Abiding Metaphors and Finding a Calling."[1] In the essay, Trethewey meditates on her upbringing as a child of a white father and Black mother. It is here that I first saw these lines from Robert Frost's essay "Education by Poetry":

> What I am pointing out is that unless you are at home in the metaphor, unless you have had your proper poetical education in the metaphor, you are not safe anywhere. Because you are not at ease with figurative values: you don't know the metaphor in its strength and its weakness. You don't know how far you may expect to ride it and when it may break down with you. You are not safe in science; you are not safe in history.[2]

The first time I read Frost's lines in Trethewey's essay, I actually did a double-take.[*] I was reading this essay for literary craft, not to study science craft. Yet there it was: "You are not safe in science. You are not safe in history."

In the essay that follows, the metaphors Trethewey centers are focused on the embodied experience of being a child of miscegenation—a mixed-race marriage between a Black woman and a white man. Trethewey writes of the abiding metaphors that govern how Black children with white biological parents have historically been interpreted both socially and scientifically, i.e., as mules, the English version of the Spanish/Portuguese "mulato." Her father believed, as Robert Frost did, that Trethewey had to understand metaphors because they are powerful mediators of the relationship between our internal world and the outer universe. Her mother also believed that an education by metaphor was necessary because "if I could not parse the metaphorical thinking of the time and place into which I'd entered, I could be defeated by it."[3] This is true for a physicist too. The beating heart of physics is creating models of the world because, ultimately, we are searching for mathematical metaphors that give us insight into our cosmos. The models that survive scrutiny become the next generation's abiding metaphors.

Abiding Metaphors

How do we learn to think about our universe as it actually is? We start with our abiding metaphors, which shape how we understand our reality. Our childhood stories follow us through life. In my case, like many Black children of the 1980s United States, I was raised on Virginia Hamilton's short-story collection *The People Could Fly: American Black Folktales*. The titular tale, which concludes the collection, opens, "They say the people could fly."[4] It is a story about enslaved Black folks escaping the horrors of enslavement by literally flying away.

In reading this story to me, my mom passed on a multigenerational Black metaphor for Black freedom dreams.[*] Because of course the point wasn't that our African ancestors who were kidnapped and forced to endure the Middle Passage were actually capable of flying. Flight was a metaphor for the freedom that was stolen from them, and it was also a metaphor for the freedom that Black people restored for themselves when they took flight from enslavement, whether by running away or through other means.

The People Could Fly is now one of the abiding metaphors of at least one physicist's upbringing, or training as we might otherwise call it. To be a physicist is to parse not just the metaphorical thinking of the here and now but also to be trained in the metaphors of yesterday, including the ones that tell stories about what we are. To understand the abiding metaphors of her family and her culture, Trethewey's essay excavates the race science that evolved to explain that people like her (people like me) are a specific kind of abomination. It's easy to understand race/racist science as a pseudoscience of the past, but not only does it live with us in the here and now, it was considered mainstream, state-of-the-art biological science right around the time that physicists began exploring fields.

When I first read through Trethewey's essay, I thought about the way the history of science and the history of racialism are themselves mixed. Specifically, I wondered about the impulse to categorize—the organizing impulse of racial classification got borrowed/intermixed/ reused in science during key developmental moments in the seventeenth, eighteenth, and nineteenth centuries. Can this be separated from the way natural philosophers—then scientists—also attached themselves to searching for principles of order/ordering and hierarchy as fundamental truths about nature?

Damascan-Ottoman polymath Taqi al-Din Muhammad ibn Ma'ruf ash-Shami al-Asadi (Taqi al-Din), and eventually French philosopher René Descartes, imagined the universe as an orderly, machine-like phenomenon.[*] The idea that the universe has an organized, hierarchical structure is its own kind of abiding metaphor. The attempt to translate humanity (and later, identity) into a mathematical equation was a fundamental political practice that also had its roots in science, and it was also a scientific practice that was driven by politics. Trethewey writes in her poem "Taxonomy" that "this plus this equals this," which is a good summary of how physicists are taught to conceive of the world.[5] Reading that line, I thought of the standard model of particle physics—we call it "the standard model" for short—which names every single particle that humans have ever detected in a collider or some other particle-detection instrument on Earth.

As I read and reread Trethewey's essay, I found myself wondering whether her critical analysis of miscegenation had direct implications for how particle physics came to be. The ordering impulse that prompted the invention of the mulatto—the human child as a mule—is the same socialized instinct that encourages me to seek out a standard model for the particle menagerie and space-time that actually is my material foundation. I wondered what other abiding metaphors I had been taught as part of my education in cosmology and particle physics and how they were permanently altering how I would perceive the world. We imagine that matter is reducible to identifiable fundamental particles (we'll come back to these later), and this is an organizing structure for our knowledge of the universe that our metaphors encourage us to arrive at.

Hierarchy is baked into how we talk about physics now. One of the major open problems in the particle-physics community is literally "the hierarchy problem" (I'll return to this in chapter 14). We don't question the name or the assumption that a hierarchy will emerge. We only conceive of difference in existence and impact through a hierarchy of strength and impact. This is what happens when you move through the world imagining that the abiding metaphors that govern your intellectual origins are synonymous with reality, when, as Trethewey says, "received knowledge becomes synonymous with truth."[6]

Hierarchy as a guiding metaphor has been useful to physicists in the past, but it doesn't necessarily always serve us—or at least serve us well. One problem with the idea that the universe is reducible to fundamental particles is that the standard model does not explain gravity. We know that gravity is in fact an effect of space-time's shape—how angles and distances are measured within it. If we imagine that space-time is a stage and the matter in it is a cast of actors, then why would reducibility apply to just the characters (matter) and not the stage (space-time)? At subatomic length scales, we might expect the weird rules of quantum mechanics to kick in.

A quantum rule that could become relevant is that every measurable quantity, like distance, has the property whereby the more you try to pin it down, the more jittery it gets. So we might expect that there are jitters in space-time, at the tiniest of scales, and that there may even be a minimum measurable distance. Why would space-time be exempt from being reduced to individual parts, just like atoms reduce to particles? Yet we experience the space we live in as a smooth, uninterrupted phenomenon, with no apparent gaps. And so far we have been unable to formulate a quantum description of space-time—a problem that I'll return to in chapter 16. But in the meantime, the way we describe particles treats them as if they exist on top of what we call a "background." Space-time lives in the back, a smooth, gapless tabula rasa where the action of particle matter occurs.

Given the metaphor I have just introduced, where the particles are actors on the stage that is space-time, a reader might create an image in their mind of a stage that never changes. But in fact, space is what we physicists call "dynamical"—it changes and mixes with time. How it changes is governed in part by how particles are moving in it, and whether particles are there at all. The metaphors sound nice on the page, but they can cause problems for our efforts to actually understand the thing at hand, which is not how to develop a pleasing metaphor but rather to understand and craft an accurate story about the inner workings of our cosmos.

The work of physics is to convert observed physical phenomena into quantifiable characteristics about its original as well as current and future status in a variety of conditions: how fast something is going, where it will be, how it will interact with a silver atom or a light wave. These are simple questions to ask, but it turns out that thinking about them gets us into trouble rather quickly, though it's the good, curious kind of trouble. Physicist Julian Barbour notes, "By its very ubiquity, motion ceases to strike us as particularly marvelous or mysterious. But the seemingly simple is complex and subtle."[7] Motion is everywhere. Blood moves through our veins, birds fly above, spiders walk onto our beds. It is often difficult to model how exactly any of this happens. Even so, physics is fundamentally driven by the idea that we can model motion—changes across space and time—with mathematical stories that reflect our physical reality.

We take for granted that anything we encounter is available for modeling because so far, it's worked out that way for us. In the case of general relativity, we have an equation that models how space-time evolved from the earliest fraction of a second until now, whenever you read this sentence. We also have a story about the dynamical relationship between space-time and particles, which are not actually like tiny billiard balls but are in fact something so much stranger that later I will tell you that actually you're just a mathematical abstraction that comes from nothing, and I will mean it in the kindest possible way. This perspective represents a profound shift in how we understand the very foundations of who and what we are. And it shows us that there's no guarantee that our abiding metaphors are good ones.

What Evolves?

In 1931, Robert Frost was profoundly annoyed by the ubiquity of "evolution" as a metaphor. He was so annoyed that he even complained that he tired of hearing about the evolution of cookies. Reading about this gave me pause because I'm constantly telling people that my job is to study the origin and "evolution" of space-time and everything inside of it. I'm aware it sounds grandiose, and it's a bit of an oversimplification because the physics I think about in my day-to-day job involves only things that are smaller than a subatomic particle or larger than a galaxy, and rarely anything in between (except certain types of dead stars).

But it's also the case that I actually do think about where everything came from. And I have always thought of this as an evolutionary process.

Frost had me wondering if evolution was yet another abiding metaphor, this time of my training in the field of cosmology. To resolve the question, one night I stayed up late reading definitions of "evolution" in the *Oxford English Dictionary* (*OED*). In cosmology, when we say that we study the evolution of the universe, we mean evolution as in the sense of development and development in the sense of becoming more elaborate.[8] But has the universe become more elaborate? Is the universe more elaborate now than it was 13.7 billion years ago? Elaborate as in "highly finished; worked out in detail" or more advanced?[9] Certainly the universe is now more advanced in age and structures come in a diverse range of sizes. There are huge differences between the average sizes of atoms, moons, clusters of galaxies, and so on. And these days, space-time is not just expanding but expanding faster and faster with each new moment in a phenomenon called cosmic acceleration.

This is the second time this has happened in our universe, and arguably the first time was much more spectacular. In the beginning (which may only be a metaphor), there was a brief moment when space-time expanded at a rate that rapidly increased, similar to how the cost of living soared in the early years of the Covid pandemic. This cosmic moment is, like that economic disaster, called inflation. But unlike economic inflation, cosmic inflation is a good thing, because it helped make the universe what it is today. I bring this up now to make the point that one could reasonably make the case that the universe was just as elaborate 13.7 billion years ago as it is now.

In fact, the late particle physicist Steve Weinberg titled his very popular book on cosmology *The First Three Minutes* because arguably they were the most incredible moments in the history of the cosmos. Inflation happened, particles formed—the seeds of everything that was to come were planted. In other words, the universe has always been intricate in its own way. I don't know if it's more advanced now, though certainly the structures which exist in it are more complex. So, maybe we can be specific: Structures have developed and thus evolved. Maybe Frost was wrong; maybe evolution is the right metaphor. But maybe the universe is just a shapeshifter like René Auberjonois's Odo in *Star Trek: Deep Space Nine*—never less or more than it was before and always fascinating.

Frost didn't contain his commentary to the ways in which the general public had taken up "evolution" as a perspective on the universe and the cosmos. He also had some rather choice words about Einstein's theories of relativity, which we must remember were relatively new at the time (1905 for the special theory and 1915 for the general theory). He noticed how the word "event" had been assigned a technical meaning, and he had a few *thoughts* about this. Specifically, "Everything is an event now. Another metaphor. A thing, they say, is all event. Do you believe it is? Not quite. I believe it is almost all event. But I like the comparison of a thing with an event."[10] Ultimately, Frost was a fan of the way cosmology was expanding our figurative vocabulary. In his poem "The Milky Way Is a Cowpath"—the title of which is a fun, offbeat metaphor—he wrote, "The universe of ours / Has got a razor edge."[11]

I've spent years feeling like a bad student of relativity because I have always found discussions about special relativity to be a tad dry, specifically because of this metaphor of "events." There is an online version of the Frost essay with a typographic error that suggests he compared cosmic events to art events. Now I can imagine that when a measurable phenomenon occurs in space-time, it's like a mini art show: a snapshot of space-time that I am considering as a keen observer. And that transforms it for me.

Frost actually did call what many would claim is the fundamental lesson of general relativity, that matter causes space-time to curve around it, "simply and utterly charming."[12] He emphasized one rendering of this as "something like" a curved phenomenon, as in maybe only metaphorically and not actually a curved phenomenon. This might sound like the endearing yet ignorant ranting of a poet who simply didn't understand the physics. But the aforementioned Nobel laureate in particle physics, Steven Weinberg, actively objected to what is called the geometric interpretation of general relativity—the idea that the Einsteinian theory of gravity means that gravity is a geometric effect, a literal question of the shape of space (and time). This is usually how scientists talk about general relativity (or GR, as it is known among theoretical physicists).

But contrary to what are now established cultural norms, in his well-regarded textbook *Gravitation and Cosmology: Principles and the Applications of the General Theory of Relativity,* Weinberg goes so far as to say that this interpretation is misleading:

> It is . . . not surprising that Einstein and his successors have regarded the effects of [gravitation] as producing a change in the geometry of space and time. At one time it was even hoped that the rest of physics could be brought into a geometric formulation, but this hope has met with disappointment, and the geometric interpretation of the theory of gravitation has dwindled to a mere analogy . . .[13]

In my view, Weinberg took a bit of a "shut up and calculate" approach to general relativity, and he seemed less keen on the interpretive element of the work where we try to translate the ideas into familiar language and visual metaphors. In his quip about the geometric interpretation being a mere analogy, Weinberg is actually lining himself up with Frost's own (literary) skepticism of physicists' loose invocations of metaphor—forty years before Weinberg's own time. Technically, Frost spoke of metaphors and Weinberg of analogy, but this is a little bit of a po-tay-to/po-tah-to situation. All of these literary objects live somewhere in the realm of "figurative language." And arguably analogies are a kind of metaphor, the kind that uses comparison in order to make an idea accessible. More broadly, metaphors may be less concrete and more abstract, using figurative language to make an idea clearer.

This is vague, so let me make it a little more concrete, borrowing an example from chemist Theodore L. Brown's book *Making Truth: Metaphor in Science,* which argues that metaphorical thought is actually fundamental to how scientists do their work. In his introduction, Brown carefully lays out what a metaphor is and how it works, and he gives an example using the opening lines of T. S. Eliot's famous poem "The Love Song of J. Alfred Prufrock": "Let us go then, you and I, / When the evening is spread out against the sky / Like a patient etherized upon a table."[14] Here the metaphor is between the evening sky and a patient who is under general anesthesia. Brown explains how the metaphor works: "The reader of the poem must *create* a similarity by somehow attaching to the evening sky whatever moods, feelings, and thoughts might arise from thinking of a patient lying anesthetized on a table."[15] Similarly, when we are called to consider the possibility that space-time has shape—as you will be asked to do over the next two chapters—we are also being asked to create similarity by attaching our notions of geometry to notions of movement and gravitation.

Returning to Weinberg's complaint about analogy, I have always found the position Weinberg took to be a bit strange, given that I personally experienced him as a thinker with a wide intellect and range of interests. I once sat through a dinner and listened to him discuss comparative constitutional law with the then science minister of South Africa, Naledi Pandor. So it was odd to later realize that this was a point where Weinberg was quite close-minded (though at least not offensive, like he was on the subject of Palestinian liberation). But he did raise an interesting question that returns us to Frost: What happens when we want to do more than shut up and calculate—when we try to attach meaning and comprehension to our results in a way that shapes what we think of the world around us?

This is a multifaceted problem.[*] The aspect that may concern *you* the most is how the heck this book will explain quantum mechanics to you when perhaps you don't know (and don't plan to learn) any linear algebra. This is also obviously a concern of mine, since I have charged myself with the task of explaining things to you, and you've trusted me enough to read this far. So, I have to deliver—in words, not equations. As Frost says, "Education by poetry is education by metaphor." To this I might add, education by physics is also education by metaphor. A different kind of metaphor, perhaps, but one that has a kinship with the figurative world of poetry.

Like readers of poetry, physicists often find ourselves asking, "But what does it mean?" Even though physics relies on math, I tend to think there is a difference between physics and the mathematical tools that physics relies on. The physicist's mathematical toolkit is largely different types of calculations requiring only the mathematical operations and associated words we use. Two plus three is five: I only needed the numbers, the rules of arithmetic plus the word "plus," and a conjugation of the verb "to be." This by itself is not the physics. Our work also calls for "interpretation," to make physical meaning of the results.

It's unlikely that a room full of physicists would agree on exactly what that means. But at its heart, the ask is for an answer to the question of meaning. For now, that often specifically refers to whatever it means in English, since, for a variety of reasons, English is currently the global lingua franca for science.[*] It matters whether we can find the words to convey the meaning. The point that Frost was trying to make is that unless we understand what it means to think symbolically, we will struggle to find the words we need or evaluate what is said to us.

The Equation as Metaphor

Even though we necessarily must think through and with metaphor, importantly we have to remember Frost's note that "All metaphor breaks down somewhere. That is the beauty of it."[16] We use metaphors to make stories more universally legible; even so, they have their limits. Nowhere is this more true than the biggest and oldest story there is: the very structure of the cosmos. For example, in chapter 5, I'm going to explain something called "boundary conditions" to you. I will rely repeatedly on your own sensibilities about what a boundary is, which at times does overlap with the more formal technical definition. But with some frequency, I will use metaphor to help you understand.

The concept of personal boundaries is a case in point. While we do sometimes mean physical boundaries, a personal boundary can also be related to demands on our time, energy, or emotion—like, "Don't call me outside of work hours." In this case, the concept of a physical boundary becomes a metaphor through which we understand how we want to be treated by our coworkers and bosses. Invoking "boundary" perhaps makes you think about these relationships and our experiences with them. In other words, boundaries are an essential mathematical tool, and the metaphors we use to try to understand them conceptually can make a difference.

And at first glance, it seems like social boundaries are probably not particularly useful for trying to understand, for example, the space-time boundaries that make black holes special. A black-hole event horizon is a physical place in space-time where the properties of space and time change dramatically. It is unidirectional—you can cross the event horizon into the black hole, but you can never go back. You can't even walk backward. It's a one-way ticket. There is no emergency exit from the interior of the black hole. The metaphor between social and physical boundaries seems to fail in this case—but thanks to quantum mechanics, the breakdown is more subtle than you might think. When we look at black holes through the lens of quantum mechanics, it turns out that maybe it is possible for some things to escape (more on this in chapter 15). Maybe the horizon isn't quite the boundary we thought it was; maybe it is more porous, like some social boundaries. The sense in which it is a metaphor is perhaps restored—by quantum mechanics, of all things.

Quantum mechanics being the reason something makes sense probably sounds unusual to the point of being a tall tale—most people have heard that quantum mechanics, whatever it is, doesn't make sense. The most famous example of this is the quantum cat in a box.[*] When the box is closed, you don't know if the cat is dead or alive. Then when the box is opened and the cat is observed, it is either one or the other. When the cat is not being observed, its state is indeterminate. That doesn't make sense, because it doesn't sound like the way the world works, but the question of what happens to the cat goes to the heart of how we interpret indeterminacy in quantum mechanics—something I'll discuss quite a bit in Section 2 of this book, "Queer Phenomenology."

Quantum indeterminacy isn't the only example of quantum mechanics violating traditional notions about how the world works. One of the quantum realm's most striking features is the phenomenon where particles are also waves, known in physics as wave-particle duality. Even if you don't really know why that feels like a contradiction, you may have heard it's a big deal. The reason it's a big deal is that particles are discrete, point-like objects. Look at the period at the end of this sentence. That's a point.[†] We think of particles like that, easy to identify and locate in space, like tiny little billiard balls. A wave is a different story. You have a sense of the wave. Maybe you've been to the ocean or seen it in the movies—waves roll toward the beach continuously. The waves are spread out, not localized to a point. A wave and a point can't be the same thing, we might say. *Well, actually, they can,* quantum mechanics retorts. The metaphors loop around one another: The ocean is made up of particles, so its waves are also made of these point-like objects, which are also abstract, quantum-scale waves.

When I refer to particles as subatomic billiard balls, maybe like me you can hear the sound of them bouncing off each other, rolling off in opposing directions. You might also hear the sound of a baseball colliding with a bat. There's a sense of hard materiality to it. Now consider waves colliding. They don't bounce, instead rolling through each other. You can see this in a cup of water if you disturb it in two different locations. Two different waves are created and when they meet, there is no bouncing. There is nothing that we would describe as a collision, at least compared to Brooklyn Dodger Jackie Robinson hitting yet another home run at Ebbets Field. There the bat met the ball, sending it hurtling over the field at over 100 miles per hour. Waves, by contrast, calmly overlap, merge, and transform each other. Yet somehow, those of us who study quantum mechanics must figure out how to merge the idea of a home run with the push and pull of the ocean. Waves are a metaphor you can literally dive into; points, not so much.

Wave versus baseball: Quantum mechanics feels like metaphors clashing. The equations, which are at the very least intended to be mathematical analogies for the real world, don't translate well into our conceptual vocabulary. And frankly, we haven't been able to develop a theory that does both at the same time, yet—our metaphors have failed us, or perhaps it's better to say that we have failed to find the right one. Whatever the case may be, without metaphor we struggle to craft a complete story, despite having something written in the language of mathematics and which we know how to calculate with.

Metaphor isn't just a useful tool for communicating to general audiences about science; it is part of how we make sense of science, part of how we make science. And it is important to note that it is *we* who make the science. There is a tendency to talk about science as if it is a thing that exists outside of scientists; to mistake the descriptions we develop to describe the universe for the universe itself. But the reality is that we scientists are story-crafting. We are using specific rules, a collection of methods that all bear some resemblance to the archetypal scientific method. Nonetheless, we are also creating stories. Every equation we write down in physics is a relationship between symbols and—we hope—some physical phenomenon. A story that we can translate. Scientists are world-building, and in the case of cosmologists and particle physicists—those of us who study the origin and evolution of the universe and both the smallest structures (particles) and largest structures (galaxy clusters) within it—we are literally universe-building.

I don't think it hurts science to admit this, if only because there is even a line of philosophical thought that argues specifically that it is our nature to do exactly this. Jamaican philosopher and novelist Sylvia Wynter once told Black studies theorist and geographer Katherine McKittrick in an interview:

> The paleontologist Juan Luis Arsuaga proposes that the human is not only a languaging being but also a storytelling species. In my own terms, the human is *homo narrans*. This means that as a species, our *hybrid* origins only emerged in the wake of what I have come to define over the last decade as the Third Event. The First and Second Events are the origin of the universe and the explosion of all forms of biological life, respectively. I identify the Third Event . . . as the origin of the human as a hybrid-auto-instituting-languaging-storytelling species: *bios/mythoi*.[17]

Here Wynter points out that while we are biological in nature (*bios*), our species is fundamentally also organized around the practice of making narrative (*mythoi*). The fact that we use language is not incidental but rather central to our existence. If we interpret the work of scientists and the way we depend on metaphor through the framing offered by Wynter, then to do science is a logical manifestation of the human storytelling tendency. There is another implication too: that we can only do science through story because story is the mechanism through which we understand the world.

Physicists are aware that this is part of what we do. And actually, the abiding metaphors of the Western world worried mid-twentiethcentury physicists. As the picture emerged of a universe that began in a Big Bang, a nothing that formed into something, some people recognized Genesis itself. Known in Hebrew as בְּרֵאשִׁית (Bereshit) and adopted by Christians and Muslims as holy scripture, the first book of the תּוֹרָה (Torah)/ تَوْرَاة (Tawrat)/Old Testament has a suspiciously similar story. There were those who worried about the overlap, the possibility that science was being read through religion at the expense of the careful techniques that ought to undergird scientific practice.

Ironically, the similarity to a religious origin story became a reason to question the one that all scientific evidence pointed to. The abiding cultural metaphor of most professional physicists at the time—the idea of the universe being conjured *somehow* out of nothing—became a factor in how the latest cosmological theories were tested and interpreted. The stories we tell ourselves matter, and they are part of how we evaluate the new stories that we are exposed to during our individual and collective journeys across space-time.

Sometimes these stories are about science and sometimes they also use science to incredible effect. I fell in love with one of my all- time favorite novels, *How to Live Safely in a Science Fictional Universe* by Taiwanese American writer Charles Yu, because of the way Yu uses Einstein's theory of general relativity as an allegory for the difficult relationship between a father and son. Drawing directly from the theory of general relativity, the book is filled with passages about men who are "pulled into the past" by either "gravitational memory" or "narrative reference."[18] Yu's novel brought to life the many ways that theoretical physics not only contributes to our intellectual life but also nourishes our emotional and artistic lives too. It also shows us how developments in our understanding of space-time can give us new metaphors for our personal journeys.

The cosmic importance of metaphor and storytelling as methods of communication is likewise beautifully highlighted in the 102nd episode of *Star Trek: The Next Generation,* "Darmok." In the episode, Captain Jean-Luc Picard (Patrick Stewart) ends up marooned on an alien planet with an alien captain whose language he does not speak. His universal translator fails him, unable to make sense of Captain Dathon's (Paul Winfield) repeated statement, "Darmok and Jalad at Tanagra." The two captains, forced to find a way to survive together with few supplies, struggle to communicate. Eventually, through different expressions of storytelling, gesturing, and repetition, Picard begins to understand that Dathon is telling him a story about two warriors, Darmok and Jalad, who are marooned on the island of Tanagra—two men like themselves. The Tamarian language, Picard learns, is expressed entirely through allegory and metaphor; Dathon needs metaphor to talk about his own experiences.[*] This episode serves as an affecting reminder that even if we don't come from the same planet or speak the same language, "the dream of a common language" (as poet Adrienne Rich put it) can be made real.[19]

If the episode "Darmok" is about the importance of metaphor—even in a technoscientifically advanced twenty-fourth century where humans are a spacefaring species traveling at speeds that break the laws of physics as we know them today—then part of what we learn from it is that to live, communicate, and be safe in the technoscientific future, we must be familiar with the figurative. Indeed, from the early twentieth and twenty-first centuries, Frost and Trethewey have already explained how two beings like Captain Picard and Captain Dathon can survive once science has brought them together: through cultural origin stories and the abiding metaphors of their childhoods.

Science and language cannot be separated. In his essay “Poetry and Knowledge,” Martiniquais and French poet Aimé Césaire explained that “Physics classifies and explains, but the essence of things eludes it.”[20] Yet knowing physics can also enrich our experience of poetic metaphors and get to their essence. We see this in how changes in scientific knowledge over the last century shift our reading of Langston Hughes’s 1926 poem “Harlem Night Song”: “Stars are great drops / Of golden dew.”[21] This beautiful metaphor, crafted just decades before scientists began to understand the way in which dew is literally made from star stuff, reads more richly now because we understand that it’s not just a pretty idea, but also the inversion of a literal one. We’ll get to how that idea works in chapter 17, “Cosmic Energy,” which is also about a fundamental concept that we still don’t understand.

Physics is like this: full of things we know side by side with things that are hella confusing. I hope to be a good guide through it, but I want to remind you that there may be a lot of concepts in this book that feel confusing at the start of a chapter, and still seem fuzzy or inconclusive at the end. That’s because physics is unsettling. It reveals to us that the universe is bigger and even more queer than what we might have otherwise imagined. We rely on the idea of space, but we don’t know what it is—physicists and philosophers still disagree among ourselves about whether it is even a material phenomenon. We know that actually to comprehensively describe space, we need to shift to space-time and understand that time is not separable from space. Even so, we humans have a strong sense of chronological time; a sense that events are sequential, and the order of their occurrence is irreversible. My increasingly elaborate skincare and haircare routines indicate that I am experiencing chronological time daily, the evolution of my body its own metaphor for what it means for time to “pass.” But scientists don’t yet have a truly comprehensive understanding of what “time” fundamentally is—an issue I will return to later in chapter 10. Physics also calls us to reinterpret what counts as intuition. Later I'll describe nontrinary neutrinos and nonbinary mesons; the fact of such particles challenges the idea that being non-binary is somehow unnatural.

In his essay, Césaire proclaims, "At the root of poetic knowledge lies an astonishing mobilization of all human and cosmic powers." Poetry and physics together give each other meaning—and to return to Anton Hur's *Toward Eternity,* this is how we write ourselves.[22] By putting ourselves through the paces of trying to understand these and other questions of the cosmos, we learn how to think and how to make sense of what it all means. To ask questions about fundamental physics is to grow our capacity to engage the world around us, to seek new storytelling frameworks and language for that which we do not yet but wish to understand. Especially now, in this moment of ecological crisis that requires all of us working together to meet it, we need everyone to develop and nurture these skills and a willingness to consider that there is more to the universe than we were taught to think. Literature and visual art help us stay in touch with this way of being with the universe—and science can too.

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* I first read Trethewey's essay in a craft book, *How We Do It*, edited by Jericho Brown. There it had the apt title "On Abiding Metaphors and Finding a Calling."
Go to note reference *

* I encourage you to spend time with Robin D. G. Kelley's *Freedom Dreams: The Black Radical Imagination* and Ruha Benjamin's *Imagination: A Manifesto*.
Go to note reference *

* The overlap between al-Din and Descartes teaches us that people across wide geographic distances can develop similar curiosities and draw similar conclusions. This fact should challenge the racially essentialist notion that mechanism—and associated ideas about time—originated only from European perspectives on the physical universe.
Go to note reference *

* Here, in using "multifaceted," I have invoked a structural metaphor that has become idiomatic in modern English.
Go to note reference *

* Of course, I should note that my analysis of how metaphor works in science is limited by the fact that I only have academic facility in one language. There is much more to be seen and heard when these concepts are understood through other languages, I am sure.
Go to note reference *

* This is more popularly known as Schrödinger's cat, but for (easy-to-find) reasons related to the person involved, I prefer to avoid his name where possible.

Go to note reference *

† The idea of a point particle is an idealization because if we zoom in closely or pull out a magnifying glass, you can see it's a bit spread out across the page. But hopefully you get the idea.

Go to note reference †

* Of course, metaphor and allegory aren't quite the same thing, although both are literary devices that use figurative language and symbolism to illuminate an idea or convey meaning. An allegory is usually in the form of a story, and it can be taken literally even though the reader/listener has a richer experience when they look for deeper meaning within the narrative. Metaphors—and related similes and analogies—compare two things that may not be, at least on the surface, alike. While there is a difference between allegory and metaphor, they are connected in terms of the effect and utility they have in human story craft. I've seen the suggestion that allegories are extended metaphors. This seems like the right way to think about it, and I suspect most of our best stories are chock-full of or undergirded by metaphors—as we see in "The People Could Fly."

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CHAPTER TWO

THE VOYAGE HOME

In which we realize that we have no fucking clue about "space"

When I think of the word "space," in any context, my brain completes the rest in the voice of William Shatner's Captain James T. Kirk doing the opening monologue to *Star Trek:* ". . . the final frontier. These are the voyages of the starship *Enterprise*."[*] *Star Trek* also figures in my earliest memory of seeing a film in a movie theater, in 1986. As a toddler, I saw "the one about the whales," *Star Trek IV: The Voyage Home*.

In the Leonard Nimoy–directed film, the crew of the *Enterprise* journeys not only through space but also time, to the 1980s when the humpback whale was in danger of extinction. I remember watching the science officer Spock, portrayed by Nimoy, swim with the whales and find a needed peace in community with them. There is a mirror image in the movie, a metaphorical link between the majesty and mystery of outer space with the wonder and enigma that is Earth's oceans. The film was intentionally on an environmentalist mission to save the largest mammals on Earth from extinction. The message I received as a four-year-old: Space is enormous, magnificent, and mysterious. And it is our home.

The Voyage Home is the first time I remember being exposed to both the reality and abstraction that is "space." It was my entrée into the kind of magic and wonder that we attach to the idea of the heavens. As Tao Indigenous writer Syaman Rapongan—of Orchid Island, Taiwan—says in the opening of his short story "The Eyes of the Sky," translated by Tim Smith: "The ocean is a starry sky, and the starry sky is an ocean."[1] These are depths that are challenging to know without using both patient observation and technology.

We tend to think that space is out there, away from us, not here in the room or on the beach or plane with us. At the same time, we take for granted that we exist in space: We take measurements. We move around. We wake up in the morning and brush our teeth without worrying about where it is that any of this action is happening. We read the news and scroll through social media and have so many concerns about the world, including whether the whales are going to be okay as the oceans warm. As we do increasingly more of this kind of activity in "digital space," it's easy to forget that all of our texts, emails, social-media posts, and other electronic communications have a physical presence not only on our personal devices but also on servers that consume energy, water, and other natural resources that go into computing equipment. Everything, even fleeting digital phenomena, has a physical existence somewhere in space.

It is disorienting to consider the possibility that we have no idea what we really mean when we refer to "space." But for me, it has also been freeing.

Stand in the Space Where You Are

Where are you? You might think this is a geographic question and answer something along the lines of: El Sereno, Los Angeles, California, United States, North America, Earth, Solar System (a bit generic, no?), outer arm of the Milky Way, Local Galactic Group, Universe. A perfectly normal address, even if it is a bit long.

Now think about the question in more abstract terms. I don't mean something like the Basement Jaxx question "*Where's your head at?*" (We know the answer to that one, anyway—in a book!) Specifically, I am talking about the metaphysical question of where your existence takes place. One possible answer to this question is "reality." But what is the nature of reality? What are its foundations?

We might say: Reality takes place somewhere and sometime, and we are trying to understand that somewhere and sometime. My gut says that a compelling follow-up question is "Where is somewhere?" and another is "Which time is sometime?" This last question might seem unnatural to you, because we have a deep-seated, socialized, and physically intuited sense that there is one timeline. We feel like we are in it alongside everyone else we know. We live in time-as-it-endures, which goes back into the past and comes down to the present, which is always marching forward to another, newer present.

The question of "Where is somewhere?" on the other hand, is quite old. Over two thousand years ago, during the Warring States era of a region now contained in China, philosophers crafted two texts that link together space, time, and the idea of a greater cosmos. One, the *Zhuangzi,* is considered one of the founding texts of Taoism. In it, philosopher Zhuang Zhou says, "What has solidity and resides in nothingness is the cosmos-as-it-extends. What grows older but has no root or tip is the cosmos-as-it-endures."[2] It seems the *Zhuangzi* is making a distinction between that which has space-like characteristics, and that which has time-like characteristics: Space extends; time endures.

We see something similar in the second text, the collection of scholarly debates known as the *Huainanzi,* which says: "What goes back into the past and comes down to the present is called the 'cosmos-as-it-endures.' The four directions and above and below are called the 'cosmos-as-it-extends.' The Way is between them and no one knows its place."[3] I find the last part of this mysterious—what is the Way? Is that the cosmos-as-it-endures-extends?

These texts are over twenty centuries old, though the translation into English that I quoted is a mere half century old. In the book where I first read them, *Later Mohist Logic, Ethics and Science,* A. C. Graham explains how philosophers of that time period went from using two pictographic ancient Chinese characters that roughly translated as "the cosmos as it extends" to a pair that used the same character for space, but together with a new partner translated as "space-duration." This transformation—and the many historical and linguistic questions that swirl around it—reflect evolving sensibilities about the nature of space and time. Specifically, in 230 BCE, philosophers were changing their views about what language might best describe space and time, and today, translators using faded scraps in an ancient scriptural dialect are still trying to work out what the philosophers who wrote the original words really meant.

Space presents a profound and perhaps surprising conceptual challenge for us. In what sense does it exist? I can wave my hands around and insist that all of this around me, around you, around this book in whatever form you have it, is space. My immediate reaction to the question is to say that space is a container filled with “all that is, or ever was, or ever will be,” as Carl Sagan once wrote of the cosmos.[4] This is unsatisfying, though, because it sets a boundary around questions of composition. Using Sagan’s language, I can ask about what comprises the phenomena that occur inside of space. But I also want to ask about what makes space itself. No matter what other physics problem I work on professionally, this basic one is always lurking in the background.

We might try to pry the question open with an abstraction. The one I was taught first is credited to French thinker René Descartes, who established a framework that we know as “Cartesian coordinates.” In this Cartesian picture, space is made of points that can be labeled with coordinates, numbers that uniquely identify the points. The labeling of the points—or at the least the potential to be labeled—gives us a sense of the existence of space. The space of everyday human life has three fundamental directions. These are what the band R.E.M. refers to in their song “Stand,” when they say, “*Now face north / Think about direction, wonder why you haven’t before.*” North/south and east/west correspond to two of the three directions.

More generally, we might label the three different possible ways to move in space as: up/down, left/right, backward/forward. Cartesian coordinates then label how far up or down, how far left or right, and so forth. This particular rendering is what we call “linear,” a word you can try to interpret literally in English: line-ar, as in line-like. To get from one point to another, we follow a straight line in the up/ down direction, another in the left/right, and another in the backward/forward. By adding these linear movements together, we can describe relocation from one part of space to another. It can be easy to say that this is functionally how space is defined, what space is—a collection of Cartesian coordinates.

But this is not always the most convenient way to label space. There are other, curvilinear systems—note the curvi-, as in curved. For example, when we want to track the movement of stars in the night sky, a system using coordinates based on straight lines—a linear system—is the worst way to do it, because the stars are moving on curved pathways. As a result, the Palikur people in the Amazon region use a curvilinear coordinate system that they developed to mirror the shape of the giant anaconda snake, which has historically been abundant in their local ecosystems.[5]

It's easy to treat a coordinate system as the definition of space. But I just defined coordinates as a set of labels—labels we provide to help us identify different locations in space. Coordinates can be very valuable, but do they have physical meaning, or do they just give us a vocabulary for referencing the thing we want to discuss? Surely it can't be that space is defined by the labels we happen to give it, right?

Let's step away from the physical problem for a moment. In formal mathematics, which concerns itself with careful definitions, a *space* is defined very carefully—it is a collection of objects with relationships governed by clearly prescribed rules. Those objects can be numbers, like coordinates. When I talked about moving up/down, then left/ right, then backward/forward, I was describing a space where one rule is that it doesn't matter what order I make those movements in; I will always end up in the same place. Technically, if I have a three- dimensional space and add a fourth dimension that I call time, from the position of abstract mathematics, this is still a "space." The idea of a unified space-time, which emerged in the twentieth century as a key idea in physics, is technically still just one type of mathematical space out of many.

In physics, we use these mathematical formulations to make models of physical space. It *does* seem that the universe is structured around a set of cosmic rules that mirror the mathematical ones that govern mathematical spaces. The universe seems to be a physical manifestation of the abstract mathematical constructs that we conjure in our minds and describe using language. This is an interesting and perhaps troubling coincidence. If I'm being honest, I feel safest in this retreat to relying on an entirely abstract definition of space, one that is set apart from concrete reality. But I also know that it is incomplete. Another way of thinking about it is that our formal mathematics is only reflecting our physical world. We haven't really abstracted from it.

In *Space from Zeno to Einstein: Classic Readings with a Contemporary Commentary,* Nick Huggett gives a confident definition of space as "to a first approximation, that in which all physical things are found . . . Everything physical that exists exists somewhere; space is the collection of all the 'somewheres.' "[6] Huggett suggests that all of physical science presumes this particular notion of space: "Mechanics—the science of motion—assumes that things change their places in space." And of course, we all live our entire lives intuitively understanding that things change their locations in space. We also experience on a daily basis that there are certain rules that seem to govern how those changes can happen—even the *Star Trek* technology of teleportation has an apparent scientific basis. To try to develop any technology like this, there are certain assumptions that would underlie the work, one of which is that space is a collection of linked somewheres and that material objects can change their somewheres through motion.

Motion is still another way to understand space: through the lens of what happens inside of it. Caught in between these questions of abstraction and practicality is the fact that journeys in space can and do happen. Conceptualizing space is intimately connected to the question of motion and movement. If we take for granted that there are these three directions in which action can occur, then we must consider what could possibly drive the action. Motion links space and time.

Descartes is often credited with this distinction between space and what's inside, which is funny because his own writing indicates that he didn't quite see it that way. He followed the Platonic line of thought. Plato, a philosopher from the Balkan peninsula of Asia, first suggested in *Timaeus* that the nature of space "is to be available for [any element] to make its impression upon, and it is modified, shaped, and reshaped by the things that enter it."[7] Plato meant that the various somewheres that comprise space had very specific shapes, and, as it turns out, he was wrong about that. But the way he frames this in *Timaeus* overlaps so strongly with Einstein's later conclusion about how matter curves space-time that Plato reads as downright prophetic. In Plato's iteration of the cosmos, there was, as Huggett calls it, the action-reaction symmetry of space and matter reacting to one another simultaneously, like dance partners producing rhythm together. Einstein's relativity—which I'll discuss in the next chapter—comes to the same conclusion.

Plato was grappling with the materiality of the cosmos and how this might relate to how motion works. Materiality is another one of those things that we tend to take for granted without stopping to think about whether we really understand it. A definition of materiality can feel tautological; according to Wikipedia, which *can* be a helpful starting point, "A material is a substance or mixture of substances that constitutes an object."[8] That sounds fine at first, but then if we tried to define an object, we'd probably want to say it is something like a substance that is material in nature—which is to say, we know a material object when we see and/or feel it. Our body, tree bark, the energy contained within sunlight, the momentary crest of a wave at the beach: These are material phenomena that we have witnessed or experienced in some way.

We can consider the possibility that space is defined relationally, by the relation between objects within it. So, space is a thing to the extent that there are objects in different places and space defines that difference in places. Personally, I think you should not feel satisfied by this explanation, because it takes space outside the realm of the physical and makes it completely abstract, as if space is a set of necessary labels and nothing else.

Isaac Newton saw it differently, proclaiming that space is absolute—a stage where the action takes place. In Newton's universe, space is an unchanging set piece, unaffected by matter's performance in the foreground. Newton arrived at his strongly held ideas about the nature of space in part by using astronomical data collected by colonial expeditions. These expeditions in turn relied on Indigenous knowledge-holders to establish how to rigorously carry out the observations that Newton eventually put to work in service of understanding what exactly happens in space.[9] This context can, on first read, seem like a footnote to Newton's philosophical interventions, but they also provide a context for his belief that he could make universalizing statements. The colonial approach Europeans took to collecting and collating information was predicated on the idea that their sensibilities were universal and absolute. This applied not just to precepts about land ownership and use, but also motion.

~~Newton's~~ Mozi's Law

Motion is the first subject I formally learned as a physics student. As a fourteen-year-old, I read *The Cartoon Guide to Physics* by Larry Gonick and Art Huffman, and learned that introductory physics was practically a different language from the particle physics and cosmology that captured my attention as a ten-year-old. Rather than introducing me to the world of black holes and quantum particles, the *Cartoon Guide* initiated me into the world of Newton's three laws. Gonick and Huffman weren't being weird; they were following the well-trodden path of physics pedagogy. Thirty years later, it's still the case that nearly every physics student around the world begins their formal education with Newton's first law. And I begrudgingly admit now, with good reason.

The I. Bernard Cohen, Anne Whitman, and Julia Budenz translation of Newton's Latin text *The Principia, Mathematical Principles of Natural Philosophy* gives what is popularly known as Newton's first law of motion in English: "Every body perseveres in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by forces impressed."[10] This is an older-than-now way of saying that every object that is at rest will stay at rest, and every object that is moving at a constant speed and direction will continue to do so. Without some phenomenon to dictate a change, stuff will keep moving or not moving the way it was already moving or not moving.

This kind of reads like a nothingburger, but if you think about it, would you have assumed that this is the way the universe works? I have never, in my everyday life, seen an object continue to move no matter what. It turns out that's because something always impedes it—think about air filling a parachute as Tom Cruise does his millionth *Mission: Impossible* stunt. He slows down because a phenomenon—air—dictates a change to his movement. But the idea expressed in that first law of motion is incredibly important. This first law is closely connected to the principle of inertia, which is defined by Newton in *Principia* as:

> Inherent force of matter is the power of resisting by which every body, so far as it is able, perseveres in its state either of resting or of moving uniformly straight forward . . . Because of the inertia of matter, every body is only with difficulty put out of its state either of resting or moving.[11]

In other words, matter fundamentally has the property of resisting motion or stopping motion, and this property is called inertia. This sounds like a restatement of the first law, but it is now mixed in with another one, introducing inertia, the property of resisting change.

This seems natural enough. Think about Sisyphus trying to roll a boulder up a hill. That seems hard because the boulder is massive and the Earth is pulling it downward—it has inertia against any application of force that counters the Earth's force. The boulder only goes somewhere if Sisyphus is able to continuously apply a force to it. This invites us to think that maybe motion is only possible if there is a force to apply it. Indeed, another Balkan peninsula philosopher, Aristotle (who was born in 384 BCE), thought the only way for an object to have any kind of motion was for a force to be continuously applied. But he was wrong.

Across the continent in a region that bordered the Yellow Sea, his near-contemporary, Mozi of the Zhou kingdom (who died in 391 BCE), had already worked out some version of the law that we typically credit to Newton. In the philosophical text the *Mo Ching,* Mozi and his followers wrote a series of statements and explanations that you can think of as philosophical statements; claims about how the world works. Some of them are about ethics, some of them are about optics, some of them are about space, and some of them are about motion. Consider one canon statement, as translated by Ian Johnston: "Movement is a change of position."[12] This is a clear definition of motion, an abstraction of something that we otherwise might take for granted and never have to explicitly spell out.

In at least one case, it's hard to know whether a statement in the *Mo Ching* was about physics or ethics—which leads me to believe that the Mohists, as they are called, might not have made that distinction the way that professional physicists today do. There is one statement (called a Canon) and Explanation pairing that has been identified by scholars as an early statement of what we now call the principle of inertia, and which Newton is often credited with first articulating. Here is the Canon (C) and Explanation (E) in question, as translated by Johnston:

> C: Stopping is by means of duration.
>
> E: Stopping: Not stopping when there is no duration corresponds to "ox is not horse" and is like "an arrow passing a pillar". Not stopping when there is duration corresponds to "horse is not horse" and is like "a man passing a bridge".[13]

Let's focus exclusively on the ox and horse. This might sound funny to you because, quite obviously, an ox is not a horse (see Figure 2.1). Why does that need to be stated? But the point is actually a deeper one: The *Mo Ching* is using our intuitive understanding that horses are a distinct category from oxen to help us develop a new intuition for the categorical difference between "stopping" and "duration." It is saying that physically, these phenomena are linked but have different fundamental natures. And indeed they are: Stopping is an action, duration is a measure of time. The *Mo Ching* is also using metaphor to teach us how they are linked. Duration occurs in the scenario when there is no stopping. The inverse is also true: When there is stopping, duration is not occurring. The *Mo Ching* is trying to convince you that this is not just a perception but a feature of our physical world, one with a rational foundation for belief.

Figure 2.1. As you can see, an ox (left) is, in many ways, not like a horse (right).

Johnston's translation is the most recent in English, but it isn't the only one. Different translations give us insight into the ideas at work, a reminder that metaphor doesn't port easily between languages, especially when they're from different times. Nearly half a century before Johnston published his, Joseph Needham interpreted the canon (C) and explanation (Cs)[E] as follows:

> C The cessation of motion, is due to the (opposing force) of a 'supporting pillar'.
>
> Cs[E] If there is no (opposing force) of a 'supporting pillar' the motion will never stop. This is as true as that an ox is not a horse. Like an arrow passing through between two pillars (without anything standing in its way, and following a linear motion without changing its direction). If there is (some kind of) 'supporting pillar' (some other force interfering with the motion), and nevertheless the motion does not stop (it may still be called motion but it will not be linear motion because there will have been a deflection). This is a case of something being 'a horse and yet not a horse'. It is like people passing over a bridge (i.e. they have to climb up to the top of the arch and down again, though they continue in motion).[14]

Don't worry too much about the details. Even if these particular metaphors seem distant to us now, they would have been relevant and relatable to contemporaries of the writers. The main thing I want you to pay attention to is how, in this translation, what becomes clear is that there has to be a reason for motion to cease. This implicitly suggests that, otherwise, an object in motion will keep going. It's obvious why someone might think that this seems fairly identical to Newton's first law and the principle of inertia! The other layer to notice here is that the *Mo Ching* uses metaphors from day-to-day life to introduce the abstract—the only way out of confusion is through metaphor. The lesson the metaphor is meant to teach us is that things will keep doing what they are doing, unless a force actively causes them to move otherwise.

The power of the Mohist approach to this law of physics is that it uses motion to highlight the apparent distinction between space and time (and this alone is a good argument for changing the name to the Mozi–Newton law, at the least). One of the reasons physics students start their education with motion is because at its core, movement is change: changing positions in space, typically over periods of time. In other words, motion becomes space and time—two different types of duration—in conversation. This is a deep statement. And we also have some everyday experience with the phenomenon. When I tell someone that I am twenty minutes away from my destination, I'm effectively measuring distance in terms of time. On the other hand, if I reported the length dimensions of a bookshelf to my friend in seconds, they would be very annoyed and likely find the numbers I've given them to be useless because they aren't used to measuring wall space by how long it takes to walk that distance. That said, if you consider that measurements of space and time are just size measurements, then we can think of some general sense of "length" in durations of space and durations of time.

This weakening of the distinction between space and time might seem like a philosophical trick disconnected from the realities of life as we experience it—where there appear to be three spatial dimensions and only one time, and in space we can move forward and backward while this is never physically possible with time. And it's worth paying attention to the extent that the distinction between the two is an artifact of language and culture. As a Jew, I use biblical Hebrew in prayers regularly, and many of them contain the word עוֹלָם (transliterated as "olam"). This word can be translated to mean "the world," "the universe," and also "all of time." The Jewish tradition already understands the cosmos as a space-time.

The merger of space and time is a place where my Jewish ancestry and my African lineages meet. Rwandan philosopher and Catholic priest Alexis Kagame points out in his essay "Empirical Apperception of Time and History in Bantu Thought" that in the Bantu language family (which covers around four hundred ethnic groups spread across twenty-four African countries), the verb "to be" is always spatial as well as temporal.[15] The example he gives is the challenge of translating Descartes's famous statement "I think, therefore I am." It is not possible to directly translate this quip into Bantu because the equivalent verb in Bantu is always paired with a spatializing adverb—in other words, a statement along the lines of "to be there." Bantu demands that you say not just that you exist at a particular time, but also where you exist in that time. "How is one to make sense of movement? By focusing on the coming together of space and time," Kagame argues.[16] Though his essay is about Bantu conceptions of time, it turns out that time, for the Bantu, is existentially understood through the lens of motion.

Kagame is careful to explain that this linguistic "symbiosis" is distinct from Hermann Minkowski and Albert Einstein's concept of space-time. But what interests me as a physicist is the proposition that in a Bantu social context, space and time are impossible to separate, and therefore it is not possible to talk about time without also talking about space. This seems to make quite natural the notion that there might be such a thing as space-time.

Kagame isn't alone in noticing how some African communities never seemed to fall for the space-time separation in the first place. Kenyan philosopher and Anglican priest John Mbiti noted in his influential book *African Religions and Philosophy* that it was quite common for languages across the African continent to use the same word for both "space" and "time," though critics of the book noted that he was referring to communities in the Bantu ethnolinguistic family, which don't represent the whole continent. Mbiti argues that many African communities organize sensibilities about space and time around events that take place in relation to their lands—the changing of the seasons and patterns in the night sky, including the lunar phases. Egbeke Aja makes a similar argument specifically about Igbo perceptions of space and time, noting also that in context of their oral traditions, we can understand notions of space and time by paying attention to how the Igbo cosmogony is organized.[17] They are not articulated separately but instead appear together in story, religion, and cultural practices.

While Aja joins Kagame and Mbiti in noticing that some African communities have historically not separated space and time, it's important to not essentialize their conclusions as "the African perspective" or to assume that these communities are intellectually frozen in time. Instead, these are examples of African intellectual histories that challenge the presumed universality of the Newtonian perspective. And the main lesson of all this for me, an Englishspeaking physicist who will never know who her African ancestors were? The cultural distinction between space and time doesn't necessarily exist for everyone in the same way, and this can shift our sensibilities about how abstract a definition of space might be.

Our Curiosity Matters

To ask questions about the fundamental nature of space and its relationship to what that phenomenon contains is on some level about satisfying curiosity. It is about the ecstatic pleasure of being more in touch with the universe by deepening our understanding of it. Our curiosity has the power to change culture and our sense of what the universe actually is. In the 1902 film *A Trip to the Moon,* director Georges Méliès imagined what it would be like for a group of Renaissance-era astronomers to commission the building of a space rocket and take it to the moon. The rocket doesn't require any special insulation, and the astronomers don't need spacesuits or oxygen supplies to walk around the moon's surface and caverns, where they meet a humanoid species who apparently have evolved on the moon's surface. To a 2020s-era viewer, this early work of science- fiction filmmaking may seem quite simplistic. We know there are no alien species on the moon. We understand the biochemistry of life well enough to know that it would be virtually impossible for such a phenomenon to occur, since the moon has no atmosphere. To watch science fiction from the start of the twentieth century is to do a little time traveling, back to a moment when humans understood less about our nearest neighbor and very little about what exactly would be required to make the journey beyond our planet. Even so, the film represented a new way of expressing old curiosities.

Today, we expect more from our stories. For one, we expect any storytelling that takes place on the moon—like the film *Ad Astra* or the TV show *For All Mankind*—to reflect the history we ourselves have witnessed. We know what it looks like for a human to walk around on the moon's surface, and we know that serious equipment is required. Any alternative rendering, like the one in the prematurely canceled *Moonhaven,* would involve some serious geoengineering and terraforming work. Our expectations have shifted because the average viewer's scientific knowledge base is deeper, which is to say that what we know about the cosmos has transformed our relationship with the stories that we tell about ourselves. What we know shapes how we dream.

Across generations, there persists the lingering question of why we want to know space. My position is that it is the foundation of reality, and thus we should want to know it. There is also the pedagogical perspective, which is that thinking carefully about the meaning and construction of “space” helps us to understand the ideas which presume that space works in a particular way. Returning to Aimé Césaire’s “Poetry and Knowledge,” there is the argument that the world is impoverished if it is full of science without poetry: “[S]cience loathes myth while poetry accepts it . . . Myth’s inferiority is one of precision. Myth’s superiority is one of richness and sincerity.”[18] I agree with Césaire that part of poetry’s power lies in its capacity to take myth seriously. I also see in our attempts to understand space (and time), humanity on the very edge between myth and science, using poetic forms to make sense of both, and using science to motivate new poetry. I think about Pedro Iniguez’s 2024 collection *Mexicans on the Moon: Speculative Poetry from a Possible Future,* and the poem toward the end, “A Black Hole Is a Melting Pot That Will Make Us Whole.” It is a poetic story of time and space, beginning, “After aeons of genocide,” in a place: “we are drawn together at last / on the galaxy’s rim.”[19] This is science, and it is also poetry.

These may seem like deeply philosophical abstractions, with no meaning for everyday life—you might think that understanding the details of space will not feed you or solve the colonial capitalist catastrophe that is climate change. Yet we are able to understand the possible impact of global warming through a set of equations that *assume* the metaphysical concept of space for the purposes of describing motion; in this case, the motion we are most concerned with is how pockets of atmosphere move and interact with one another—and are affected by ocean currents—producing what we call weather. In other words, our ideas about abstract space make climate-change analyses possible.

In professional physics, we tend to be particularly concerned with describing motion that has happened and making predictions about motion that could happen in the future, given a specific set of physical conditions. This is the act of creating models—schematic representations of physical scenarios—and comparing them with experiment. These models can have serious consequences: A poorly designed part can, as we learned in 2023, mean the difference between your Boeing plane getting to its destination with or without one of its doors.

We need space in order to engineer: To build a bridge is to consider how material objects might move in space and what shapes and connections between those material objects will stabilize it there. Whether we like it or not, to do the necessary calculations, we are making certain assumptions about how and where space is, and we are relying on the fact that the rules never, ever change. And as I will explain later in the book, if we want to understand phenomena like black holes, that requires examining what exactly it means to talk about space and time. This is the case not only because black holes have weird spatial effects and create distortions in the flow of time but also because black holes are the one place in the cosmos where humans kind of understand the intersection of gravity and quantum mechanics—an intersection that demands we rethink space and time.

In *The Voyage Home,* a key plot point hinges on locating places where the Starfleet crew needs to go. Communications officer Lieutenant Nyota Uhura (played by the amazing Nichelle Nichols) is responsible for providing the necessary coordinates to science officer Spock. These moments, like many we take for granted in our daily lives, highlight the fact that abstractions of space are always present for us and will continue to be, far into the future. Authorities map out our world, covering it in coordinates. We move about by understanding the coordinate systems and using them accordingly.[*] It turns out that in order to do this correctly, we also need to understand space and time together in abstract terms. This is especially true in the era of heavy reliance on a general relativistic technology, the global positioning system (popularly known as GPS).

Even if we are tempted to shun thinking about the nature of space because it's too esoteric, too apparently useless, the universe is structured in a way that constantly undercuts such material judgments. The terrifying thing about this is not knowing where we are going or where we may end up. The joy is the way practicing being disoriented allows us to experience the universe in ways no generation of humans has before. We can't draw boundaries around what knowledge is meaningful and still expect to survive or live well.

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[*] The use of the word "frontier" in *Star Trek* is fraught to say the least, since in the context of the American idiom it evokes the historical and continuing legacy of settler colonial occupation of Indigenous lands and the continued subjugation of Native nations and peoples.

Go to note reference *

* As Sarah J. Jackson points out in *A Second Sight,* we also use expressive culture to map out our world. Jackson argues that Black films like Haile Gerima's *Sankofa* function as a cultural map, showing us where and who we are culturally.

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CHAPTER THREE

SPACE-TIME IS THE PLACE

In which it turns out that space and time are not separate

In the classic Afrofuturist film *Space Is the Place,* musician and composer Sun Ra stars as a spacefaring, liberated Black being named Sun Ra. The opening premise is that he has found a haven for Black people away from white supremacy and has returned to Earth to gather a community who will populate it. "Everything you desire from this planet and never have received will be yours in outer space," he proselytizes to the camera.

A refrain that viewers hear throughout the film, in Intergalactic Myth Science Solar Arkestra member June Tyson's sonorous voice, is "It's after the end of the world / Don't you know that yet?" The film opens with this line, yet eventually lands on our planet, with all of its painful, earthly considerations of poverty, racism, misogyny, and misogynoir.[*] The world is clearly not literally over. Rather, in *Space Is the Place* there is a metaphor at work that reminds me of Virginia Woolf's call for women to have "a room of one's own," but here the creative team—led by director John Toney—are calling for a Planet of Black People's Own.[†] The metaphor works by invoking the way travel through the broad expanse of space mirrors the difficult journeys of Black people in the Americas, including the originating, torturous Middle Passage. In this allegory, the world as we know it is over, and it's time to start over elsewhere, in space.

Though "space" is the focal point of the story, time plays an inextricable role in the narrative. Sun Ra begins in 1969, travels back to 1943, goes to space, and returns sometime around the year of the film's release—1974. These narrative jumps play with the idea of time travel as both a physical and a metaphorical phenomenon. Sun Ra explains toward the end of the film, “We bring to you the mathematics of an altered destiny.” The fundamental proposition at work in this story is that Black people—and our Native kin—can transform our relationship to time and leave white supremacy in the forever past.

It’s easy to write this off as a nice piece of science fiction that is premised on suspending our sensibilities about how the physical world actually works. Time, as those of us who are middle-aged and older are especially aware, goes in only one direction—we can time-travel to the next moment in our lives, but never to any previous ones. We are *forced* into the next moment, even when we don’t want to be there. *Space Is the Place* grapples with the psychosocial impact of this irreversibility in relation to the trauma of colonialism and white supremacy. It’s worth remembering that the film’s writers, Sun Ra and Joshua Smith, were creating at a moment when space travel had become a major feature of global political culture. They were not writing outside of science but rather in reply to it, trying to illuminate the possibilities it offered. In *Space Is the Place,* time is transformed from something that marks the lengthy endeavor to survive white supremacy into a tool of Black creativity.

Arguably, this transformation is imaginable because Sun Ra and Smith were living not just in the age of humanity’s first steps beyond the Earth’s atmosphere but also in an era when humanity’s scientific understanding of the nature of reality was shifting. The first half of the twentieth century had witnessed the articulation of the transformative, though not widely understood, precepts of both Einstein’s relativity theories and quantum mechanics. Time had never seemed more fungible than in the century when its relativity was discovered.

Please Drive Non-Relativistically

When you’re doing physics, it’s valuable to maintain a clear perspective on the difference between social sensibilities about time and the physical phenomenon of chronological time. Even in the futurist scenario where we can imagine humanity starting over in the face of catastrophe—like the Middle Passage, or our current nightmare global-warming scenario—a new beginning does not mean that chronological time can be or has been reversed. This feature of time anchors what a physicist sets out to do: We want to make statements about how things are or will be at any given time. This is the state of the system, and it is premised on the idea that there is an order to time.

Ultimately, our great cosmic story relies on some kind of merger between space and time. In what sense do they actually belong together? We live our lives in what we will call the "slow regime," which is to say that even the very few who get to travel in the vehicles we have that go faster than the speed of sound are, along with all the rest of us, moving a lot slower than the speed of light. The speed of light is a key reference point because nothing material can travel faster. This is an easy enough statement to make, one that's even pretty easy for a reader to swallow. *So what, there's a universal speed limit? I wasn't trying to go that fast anyway,* you might say. But the fact of a speed limit of any kind has profound consequences, especially if you believe that space is absolute and entirely distinct from time, an idea physicists held to for the roughly two hundred years between the advent of Newton's mechanics and the discovery that the speed of light is finite, universal, and unchangeable in a vacuum.

To understand why physicists were wrong about space and time, it helps to think about one of my speeding trips to my incredible dentist, who has been helping me manage my dental care since a car/bike collision in 2002 left me with lifelong dental disabilities. The state of my car: going 80 miles per hour in the direction of southwest. Eighty miles per hour is the speed, which characterizes how much distance is traveled in a given time. The direction, southwest, tells you where I am aiming that speed.[*] Consider an implausible scenario in which Boston traffic allows me to go 80 miles per hour at each instance of an hour (as opposed to an average where sometimes I go faster and sometimes I go slower). The language of "80 miles per hour" means that if I only ever move at that rate, I will travel 80 miles in an hour. This is a statement about both time and space.

Imagine you're a passenger in the car and you've got a laser in your hand, pointing forward—because, like me, you think lasers are awesome.[*] As we drive down the highway, there are two questions we can ask about the state of the light being emitted from the laser:

1. What is the speed according to the two of us in the car?
2. What is the speed according to someone who has pulled up alongside the road to measure car speeds and occasionally pick out drivers to harass?

To understand what happens, we need to think through whether these two measurements are the same. Technically they are taken in two different frames of reference, two different perspectives from which they are making measurements. Everything in the car is moving at the same speed as me. So, whatever book I've brought along shares with me what we physicists call a frame of reference. The laser does too. In the frame of reference of the car, the laser is stationary because it is moving simultaneously with us in the car. Yet another frame of reference is by the side of the road, in a car where someone is sitting and watching other drivers.

Naïvely, one might guess that according to the person at the side of the road, the speed of the laser is the speed of our car, plus the speed the light comes out of the laser, as in "$\text{speed}_{\text{car}}$ + $\text{speed}_{\text{light}}$." And you are certain that we passengers in the car simply measure the speed of the light inside the car as being the speed at which it comes out of the laser, as in just $\text{speed}_{\text{light}}$, which is clearly slower than $\text{speed}_{\text{car}}$ + $\text{speed}_{\text{light}}$. But what actually happens is wild: Everyone, no matter how fast they are going or what frame of reference they are in, measures the light as having the exact same speed. It's physically impossible to add speed to the light, which means the speed of light is constant and *the same in every frame of reference* no matter how that frame of reference is moving relative to where the light source is.

I want you to stop and think about how weird all of this is. No other speed in the universe functions this way. By contrast, if I throw a paper airplane inside a car, I will measure it going fairly slowly, but people by the side of the road will see the airplane going roughly the speed of the car. The speed of light, on the other hand, looks like it's going the same speed—to everyone.

When experiments first made clear to physicists that the speed of light is finite and constant in all frames, people found themselves desperately trying to understand why. It was all very "make it make sense!"

Knowing what we already know, we can think through the simple implication. Imagine sending information from the present (or being in the present and receiving information). Light takes time to travel, so a signal to or from the present can only go so far in a limited amount of time. The fastest the information can go is the speed of light. So, there is now a rule governing how far away that information can be. This too is an implication of light's constant, finite speed. We can sketch out where in space the signal can be sent to and received, what is causally plausible. This is the light cone (see Figure 3.1). The light cone is a visual metaphor for how the finite speed of light circumscribes causality, what cause and effect are plausible.

In the end, Albert Einstein was the one who stubbornly pursued what it meant to have a finite, constant light speed that is the same in all frames. Using a series of thought experiments involving trains and considering the structure of the equations that described electromagnetism, Einstein proposed that this property of light required a shift in physicists' worldview: Rather than thinking of space and time as distinct, we must think of them as entities that mix.

This necessarily transforms how we measure motion. Now frame of reference really matters. Imagine someone sitting by the side of the road, using their watch to measure how long it takes my car to travel a certain distance. Their watch will show more time passing during the journey than mine does. In other words, the person who is moving measures less time passing than the person who is motionless. This is called time dilation. I realize that this sounds like nonsense, because surely we would have noticed if our watches were measuring time differently, right? But the key thing to remember is that we all live life in the slow lane—even the greatest F1 driver of all time, Lewis Hamilton. The speeds of everyday life are well below those where the effects of special relativity would ever be noticeable. As long as we drive non-relativistically, we will never notice.

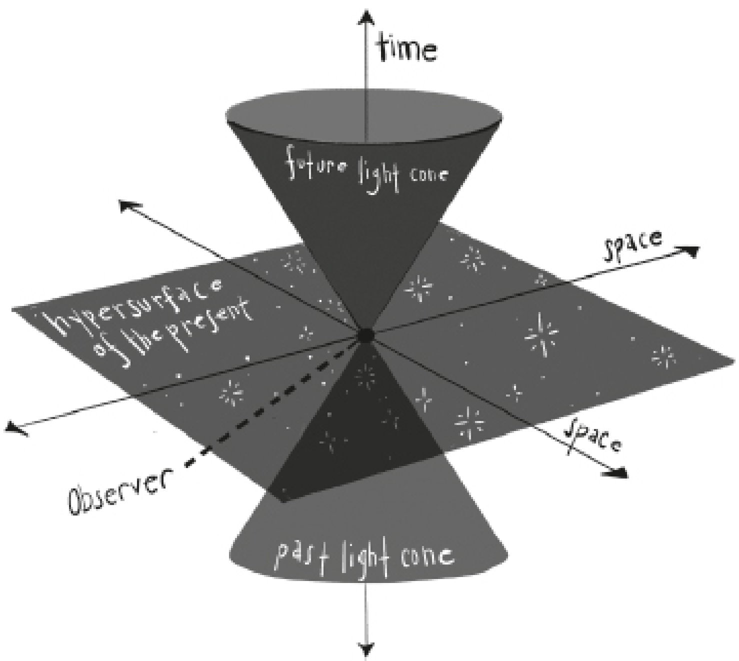

Figure 3.1. The light cone. In this image you see two cones, connected in the middle by a dot, which represents the observer. The cone opening upward is the part of space-time that the observer can communicate to in the future, given that the speed of light is finite. The cone opening downward is all the places in the past that can hope to send a signal to the observer, given the finite speed of light. The flat surface intersecting with the observer, "the hypersurface of the present," is a slice of space-time at the observer's present location.

There is a partner idea to time dilation, which is called length contraction. Imagine a scenario where someone in the backseat of my car is holding a baseball bat so that the top of the bat points to the front of the car. According to those of us in the car, the bat is stationary. We measure its length. By contrast, someone standing by the side of the road sees the bat as moving at the speed of my car. Because of relativity, they won't measure the same length for the bat as we do in the car. To them, the bat will be shorter. This apparent shortening of the bat—in the direction of motion—is length contraction. And I swear I'm not making this up. This is not only the interpretation mandated by the equations, but it is also now a well-tested outcome that is more than a century old.

Time dilation is real. Length contraction is real. These thought experiments make it clear that moving observers and stationary observers don't agree about measurements of time and space. What you count as time, I might count as space, given the right differences in our conditions. Time and space are actually inseparable.

Because extraordinary claims require careful investigation of underlying assumptions, let's notice one we haven't named. Implicitly throughout these relativistic thought experiments, we have been making an assumption about the nature of physical law: This is the working premise that the laws of physics will be the same—invariant, physicists like to say—in all inertial frames of reference. An "inertial frame of reference" means one that is not accelerating, which is to say the speed and direction are *not* changing, since acceleration quantifies a change in one or both of them. This assumption is called the Galilean principle of relativity.

And importantly, alone, the Galilean principle is entirely consistent with the concept of absolute space, distinct from time. In the scenario where absolute space and absolute time are the correct way to describe our world, someone watching me zoom by in my car will measure distances exactly the way I would, despite our differences in speed. The Galilean principle, applied to a universe with a constant speed of light, means accepting that the laws of physics are the same in every frame *if* we accept there is no space and time, only space-time. They can't be separated—they are relative.

While we've lost absolute space and absolute time, we have gained absolute space-time. If we can find a way to measure the mixture of space and time that constitutes space-time, we can in fact measure "distance" across space-time. So, in some general sense, absolute distance is preserved.

Of course, one does not simply walk around measuring space-time lengths with a measuring tape. We need a measuring tape *and* a stopwatch. In other words, when we want to establish distances in space- time, what we need is a ruler that can carry information about space and time and the way they mix, simultaneously. Mathematically, this ruler is called the metric. The metric is an equation that tells us how to measure distances. Newtonian physics has a metric associated with it in which space and time are absolute and distinct. Special relativity has a different metric. In the relativistic scenario, it becomes far more important to understand space and time as unified in one four-dimensional phenomenon known as space-time. The ingredients? Three spatial directions (up/down, side-to-side, forward/backward), plus time, now inextricably bound up with one another.

I like the way philosopher W. V. O. Quine helps us interpret this: "A man is a four-dimensional object, extending say eighty-three years in the time dimension."[1] Quine is talking about a combined notion of duration. As you've seen from the examples, different observers will make different measurements of how much duration is in space and how much duration is in time. The metric captures all of that duration, together. This might be different from how you're used to thinking about space and time.

Perhaps the easiest way to try to get at this is to consider yourself Alice down the rabbit hole, in Wonderland. Except, unlike Alice, you're never going home. In this wonderland, we live in four dimensions but can only visualize three. This makes developing intuition for it more effortful, but not impossible. We can't easily visualize it or construct some physical analogue that will give us a sensory experience of four dimensions. But you live in four dimensions your whole life. Each instance of your life is an event in space-time. Remember what Robert Frost said about this: "Everything is an event now. Another metaphor. A thing, they say, is all event."[*] Indeed, that is the physicist's claim. Your life events are all absolute locations in space- time, situated somewhere in space and somewhere in time, together.

Falling into Space with You

I want you to know that I don't know anyone who fully understood special relativity on the first try. Physics students in high schools and universities around the world do conceptually and mathematically sophisticated problems to explore the concepts at play and cement their understanding. So, if you're feeling like your intuition is a bit shaky right now, or like you might not be able to explain all of this to the enby sitting next to you on the bus, know that I don't expect you to remember everything.[*] All I want you to remember is the following: One, the speed of light is the same, no matter how fast you are going (which will also always be slower than the speed of light). Two, this implies that according to someone watching another person in motion, time ticks by more slowly for the person who is in motion. And three, the implications of this are radical—there is no such thing as an absolute sense of space that exists independent of time. Space and time, separately, are both fundamentally relative, even if at the speed of human life they seem quite independent.

The space-time that special relativity gives us—named Minkowski space for the German mathematician who first identified the mathematical structure that suited special relativity—is flat. By now, I hope I've encouraged you to respond to comments like this by asking, "Sure, but what does 'flat' even mean at this point?" Let's think carefully about our sense of "flat" in everyday life. Look at the two parallel lines on the left in Figure 3.2. Imagine they are the pathways of ants walking around.

Figure 3.2. On the left, there are two lines in parallel on a flat plane. They remain parallel no matter how far the lines go. On the right there are two lines that start out in parallel on a spherical surface, but they tend toward each other because the surface is curved.

In a flat space, by definition, they will remain parallel forever. This is one of the fundamental premises of the Euclidean geometry many of us suffered through in grade school. Two ants who are destined to each experience their life events on one of these lines will always walk in parallel to each other. If the ants live in Minkowski space and these lines are their world lines—the path they trace out in space- time—then they would also remain parallel forever (living separate lives that never intersect). This is definitional flatness. If there were any curvature present, the lines would eventually bend toward each other and cross one another. Since they remain parallel forever, they never do.

Minkowski space-time with its flat, always parallel lines, is very nice and all, but it's missing a key feature: The space-time of special relativity does not account for gravity. When we do think about the nature of gravity simultaneously with the lessons of special relativity, it turns out that ants don't live in Minkowski space at all and neither do we. We live in a space-time that across reasonably short distances looks like Minkowski space, the low-gravity approximation of the real theory that describes our cosmic tapestry. But when gravity is strong, this approximation doesn't cut it.

The reason we don't live in flat space? Gravity is curvature. It might sound like I'm suggesting that special relativity, which has been celebrated as one of the great achievements of the twentieth century, is wrong. It's not wrong. But it has its limitations as a model of the physical world. Special relativity is correct in the scenarios where it should be applied: high speeds, high energy, short distance, low acceleration, and low gravity. I write "low acceleration" and "low gravity" with the professional advantage of knowing already that these are in fact redundant statements. It turns out these two states are the same, and under the right experimental conditions, it's impossible to tell the difference.

Here's what I mean when I say low acceleration and low gravity are one and the same: The amount of gravitational force an object experiences is determined by how massive it is—how much stuff there is. Formally this is the gravitational mass, the mass that determines how gravity is experienced. Similarly, the amount of acceleration—changes to an object's speed and direction—due to nongravitational forces is determined by how massive the object is. We call this mass the inertial mass—how much mass is needed to get an object moving. You might assume that the gravitational mass and the inertial mass are the same number and it turns out they are, but this is not a given. The fact that low acceleration and low gravity are the same physical conditions is a consequence of a rule the universe seems to follow: the principle of equivalence. This principle says that gravitational mass and inertial mass are equivalent.

This is a big deal, what Michael P. Hobson, George Efstathiou, and Anthony N. Lasenby enthusiastically call "a *truly remarkable* coincidence" (italics theirs!) in one of my favorite general relativity textbooks.[2] They go on to say that there's no obvious reason why these two quantities should be the same. One describes the resistance to an applied force, where the resistance to an applied force is simply the resistance to having its speed and direction changed—resistance to what we call acceleration. The other describes how strongly an object will respond to gravity. This sounds like I'm repeating the same thing twice, because functionally I'm saying "mass equals mass," which like, sure! That makes sense. But what is actually being said is that "$\text{mass}_{\text{gravity}}$ = massinertial." In other words, in theory these could be two different phenomena but they aren't. And the equivalence principle, perhaps nonintuitively, points us to how we have to revise special relativity to land at a formulation of space-time that takes gravity into account.

When Einstein used it, the equivalence principle wasn't really a new idea. But it played a key role in helping him think through how to add gravity into his notion of special relativity. The hypothesis: The principle of equivalence means that a frame of reference with gravitational forces inside of it is indistinguishable from a frame of reference where there is acceleration occurring.

This is often demonstrated by portraying an astronaut in a rocket that is accelerating—changing speed or direction—through space, juxtaposed with a person on Earth. In Figure 3.3 you can see Gravity Girl, who first appeared in my book *The Disordered Cosmos*.[3] On the right, Gravity Girl is in an elevator sitting on the ground floor on Earth's surface—experiencing Earth's gravity—while bouncing her tennis ball after practice. On the left, she's in her *Harriet Tubman* spaceship far from Earth's gravity, accelerating. Can she tell the difference between her two frames? No.

Now consider a slightly different scenario: Imagine that on the right, Gravity Girl's elevator is several floors off the ground and descending, but not in a controlled manner. She's in free fall in the Earth's gravitational well (and thankfully, this elevator has a parachute, so she'll be safe on the other end if she holds on to the elevator railing). Now, instead of throwing her ball down, she just lets go of it. What happens? The ball hovers wherever she let go of it. From her perspective, it doesn't move at all. This is equivalent to what we might expect if she was in a no-gravity environment in outer space, with no acceleration.

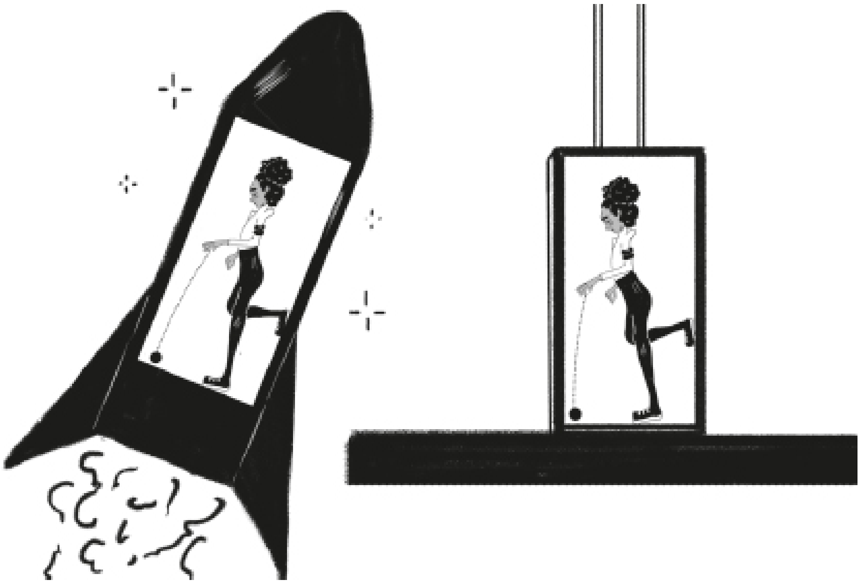

Figure 3.3. Gravity Girl experiments with gravity, as she is prone to do. From her point of view, when the rocket is being accelerated, the effect on the ball is the same as the effect of standing on Earth, where it is in the Earth's gravitational field. In both scenarios, the ball is accelerated downward relative to the rocket/elevator with an acceleration.

How can these two scenarios create identical physical circumstances? In the falling elevator, Gravity Girl and her ball are falling at the same exact rate, so relative to one another and the elevator itself, there is no motion. This is exactly like being in a no-gravity, no-acceleration spaceship. In both situations, Gravity Girl and her possessions will experience weightlessness.

Our analysis of Gravity Girl in her various spaceships and elevators involves a very careful application of relativity in different frames of reference. What becomes clear is that the laws of physics don't seem to change, even when there is acceleration involved. The other thing we are learning is that it can be impossible to tell the difference between acceleration and gravity. This part is so exciting for me that I have to say: This is really fucking wild, you guys. There's literally no difference between me hitting the gas on a cosmic freeway and all of the Earth's atoms working together to hold us down on the surface. The source of the acceleration is different—a car engine and gravitational inertia are still different—b ut inside a windowless box, I wouldn't be able to distinguish between the two.

Put more calmly, we have seen the principle of equivalence at work. And . . . you're probably wondering how that helps us understand how gravity shifts our theory of relativity. It's reasonable to consider that, at base, one of the questions lurking beneath the surface here is how gravity works. I just claimed Earth's atoms are all holding us down, but how? We know that gravity causes massive objects to be drawn to one another. The example we are most familiar with is that we are all held to the Earth's surface by the gravitational pull of the Earth's mass. The closer we are to the surface of the Earth, the more strongly we feel it. Notably, each of us, as an object that has mass, actually pulls back on the Earth; it's just that we're so low mass in comparison that we don't make a difference.

Another example is that all the planets in the solar system are orbiting the sun, held in their orbits by the effects of the sun's gravitational pull. Similarly, the Earth's moon is pulled along by Earth's gravity, joining us for our annual trip around the sun, while also experiencing an approximately twenty-seven-day orbit around the Earth itself. But what's doing the pulling? It sounds like magic, as if mass has a way of waving a wand, shouting, "Presto donezo!" and creating a gravitational attraction.

The equivalence principle forces us to take a new position on how gravity does what it does. To understand involves a few logical steps, but instead of asking you to trust me I want to explain, which I avoided doing in my last book.[*] Let's start with another way of thinking about the equivalence principle. It is saying that in any given environment in which there is gravity, all objects are experiencing equivalent acceleration and will therefore "fall" in the exact same way. In other words, the equivalence of gravitational mass and inertial mass means that all types of mass, when subjected to the same gravity (say, the force of the Earth), will experience the same amount of acceleration.

Now, imagine an observer who isn't experiencing any forces, not even gravity. Such an observer could rightfully be called an "inertial observer" from the point of view of special relativity because they are not accelerating. Next, tell this observer to measure the gravity a satellite experiences in the Earth's vicinity. But to make the measurement, the observer must be local to the satellite, which, again, is experiencing Earth's gravity. So, how can the observer be insulated from gravity? They can't be. To put it another way, the observer cannot remain inertial and make measurements of gravity. There's no way to create an observer who is outside of the gravitational system, who can observe the effects of gravity without also directly experiencing them. In other words, what Einstein found was that to develop a theory of relativity that fully took gravity into account was to recognize that special relativistic notions of the observer were insuffi-cient for measuring gravity.

So. Special relativity's flat space-time cannot possibly describe all of space-time. There is no way to absolutely measure gravity from the outside; we can only measure the relative gravity between two different locations. When we do, we find the straightest possible lines no longer remain parallel forever. Instead, they can cross eventually, and the flat space-time of special relativity gives way to a brand-new conception of space-time, one that is curved.

This general(ized) relativity comes with some exciting new effects. There is a new way to achieve time dilation in general relativity: use gravitation. If you've seen the Christopher Nolan film *Interstellar,* you might recall the scene in which some of the astronauts travel to a planet near a black hole, while leaving a colleague behind on their spaceship. Miller's Planet is a punishing environment with 130 percent of the Earth's gravity, where the presence of a strong external gravitational force (the black hole) creates dramatic tides with killer ocean waves that are higher than Earth's tallest buildings. On the surface of the planet, the astronauts only experience a short amount of time passing, less than a day. But every hour on the planet is equivalent to seven years on Earth. Thus, while the astronauts only spend a few hours on the planet's surface, their colleague Dr. Romilly on board the spaceship experiences decades alone—an emotionally devastating experience for the film's only Black character.

Miller's Planet is a cinematic example of how time dilation works. In practice, we have never had the opportunity to test such a dramatic example. But using experiments involving comparing clocks on the ground with clocks in flying airplanes, we have been able to show that someone far from the surface of the Earth will measure time passing faster than someone who is at sea level. This is gravitational time dilation, and it is due to the curvature of space-time. Our understanding of this scientific phenomenon has also radically changed our day-today lives: GPS, which is an acronym for "global positioning system," only works correctly because it takes into account relativistic effects due to space-time's curvature. If we don't account for time dilation and length contraction, it would be impossible to build a system that accurately gets us from point A to point B.

The Fabric of Our Cosmos

It's natural to want to have a tactile or visual sense of what exactly a curved space-time is. The problem, of course, is that space-time is four-dimensional, which is essentially unimaginable. Our brains only know how to "see" in three dimensions. That doesn't mean we are totally lost. There is a popular visual metaphor that can be useful here: the fabric of space-time. It is so ubiquitous that theoretical physicist Brian Greene even titled one of his books *The Fabric of the Cosmos: Space, Time, and the Texture of Reality*. This metaphor works by inviting us to think of space-time as akin to a piece of cloth. Because of our intimate relationship with them, textiles are important cultural signifiers that can help us connect with the idea of a curving space-time, as Tiya Miles explains in *All That She Carried: The Journey of Ashley's Sack, a Black Family Keepsake*. Part of what Miles maps out is how a small piece of fabric became a time-traveling token that links generations of women across both space and time. This is also how I grew up with fabric. My Grandma Elsa was an immigrant from Barbados who always sewed her own clothing, even after my family could afford to buy prefabricated garments (frankly, her designs were better). Perhaps that is why, in my head, fabric is my go-to visual for a curved space-time.

To consider the cosmos as akin to fabric is to think of an object that functions as a link, a setting. So we might say that the cosmos is a tapestry (as I actually did, a few pages ago). There is a richness to this way of looking at it. I immediately think of "I Go to Prepare a Place for You," Bisa Butler's magnificent textile portrait of Harriet Tub-man, which any visitor to Washington, D.C., can find in the Visual Arts Gallery of the National Museum of African American History and Culture (aka the Blacksonian). Tubman, who was a survivor of enslavement, used her skills as a naturalist to aid her work as a freedom fighter, whether it was helping enslaved folks self-emancipate or supporting the North's efforts in the American Civil War.

Butler's portrait uses quilting and appliqué (needlework) to reproduce a photograph of Tubman sitting in a chair; instead of the realism of photography, we get the surreal embedding and enfolding of naturalist imagery in Tubman's dress. Sunflowers, representing both the land and the cosmos through their insistent orientation toward our local star, join red birds whose flight represents freedom; in this way, Tubman becomes a tapestry in which liberation occurs, the multivalent meanings of her life and contributions embedded in her embodied presence on the fabric. The fabric is both a setting for the portrait and a manifestation of Tubman's actions as "our General." So when I think about this work in the context of the fabric metaphor, I think about the way in which Tubman is both happening on the fabric and also how the fabric is crafted out of her memory.

Of course, this is a metaphor. Space-time is not actually crafted out of conscious memory; at least, that is my own perspective as a metaphysical realist, someone who believes that reality exists beyond the conception of my mind. But metaphors always have their limitations, so we can take the fabric metaphor for what it is and as far as it goes. What the fabric metaphor can tell us is that space-time is the place where the action occurs. The question we can then ask is whether space-time is a place that is shaped by the action. It turns out that the answer is yes.

It's easy to type the word "curvature," but maybe a bit harder to think about it in the context of space-time. Because Butler's portrait of Tubman is quilted, presumably the Blacksonian curators must be quite careful in how they hang it, to keep the textile from sagging under the force of gravity. You can think of such distortions like curves in the fabric of space-time. Now imagine that to give patrons a different perspective on the work of art, the curators decided to stretch it out, parallel to the floor, held taut along the edges so that it hangs a few feet above the ground. A young Gravity Girl, accompanied by a mom who is keen to show her the brilliance of Black history and art, might come along and have a look. She loves watching historic footage of Jackie Robinson playing for the Dodgers and wants to be just like him when she grows up, so this time she's got a baseball in her hands. In her excitement at seeing the nice lady on the blanket who looks like she's got a good throwing arm, young Gravity Girl throws the baseball onto the portrait because she wants to play catch with Mrs. Tubman. The baseball has a bit of weight to it, which means that the quilt sags where the baseball lands on it. (Remember, this is a thought experiment, so no works of art have been harmed in the process.)

This is exactly what happens to space-time in the presence of a massive object. Imagine that the baseball is the sun, out there in space-time. It is bending space-time around it. And there are consequences: The planets are caught in that curvature, falling toward the sun in stable orbits. These orbits can be described fairly well by Newtonian physics, but they are more accurately described by general relativity.

My favorite rendering of the radical shift in perspective that general relativity offers comes to us from John Archibald Wheeler, who said, “Matter tells space how to curve and space tells matter how to move.”[*] I also like to say that there is no gravity, only curved space- time. Gravity is a facet of the fundamental structure of space-time. Of course, the way we experience it in everyday life, it feels like there is a gravitational force. We don’t see the curvature the way young Gravity Girl sees it on the quilt. Instead, we are borne through it. Our world lines are governed by the structure of space-time’s grooves, which are now freed from the unchanging flatness of Minkowski space. But it keeps what was exciting about the move to Minkowski space: the mixing of space and time. And now that curvature is possible, there is a whole universe of possibilities for how distance is measured and what equation might describe the nature of that measurement, the metric. Instead of the unchanging space-time of special relativity, we have one that can change as events unfold, with properties that vary from point to point across this four-dimensional cosmos.

There is an equation, Einstein’s equation, that mathematically codifies this relationship between the presence of mass, the structure of space-time, and the motion of massive objects.[*] An equation like this can describe multiple scenarios with diverse parameter inputs, what we call solutions to the equation. And as soon as Einstein published his work in 1915, scientists found solutions to these equations showing fantastical possibilities that you’ve probably heard of. In 1916, Karl Schwarzschild published a solution to Einstein’s equation that is now known as the Schwarzschild space-time. The Schwarzschild space- time describes one type of black hole, a space-time where things can go into the interior region but nothing can go out. Just a few years later, in 1922, Alexander Friedmann showed that another possibility was an expanding space-time.

To describe the ever-expanding nature of space-time, I often tell people to think about a balloon covered in dots. The balloon is the universe, and the dots are galaxies. As the balloon is filled with air, I ask my audience to imagine the stretching of the balloon, the way the distance between the dots grows. This is the expansion of space-time, with galaxies apparently racing away from each other as space-time expands between them. (I'll talk about this more in the next chapter.)

However, the reality is that the expansion of space-time is unlike anything in the universe except the expansion of space-time. This metaphor begs a series of questions. In the real world, a balloon is expanding into and through space-time, and it's being filled with a gas of some kind (hopefully not helium, since there's an increasingly dire global shortage). When I compare space-time to a balloon, I'm inviting the question of *where* it is and *what* is causing it to expand. If you were wondering about either of those things, you're not confused—in fact, you've stretched the metaphor to its limits *because* you understand it. The metaphor is a ladder that helps to shorten the distance between what you know and what you want to understand.

Space-time is, by definition, all the places that ever were or ever will be.[*] Today millions, maybe billions, of people live out their lives knowing that space-time is the place where we all live. And this space-time is not static: It's dynamic. It's changing. It has black holes. And it's expanding, from ______ (undefinable) into _______ (undefinable). Every story that has happened or is going to happen will happen on what we call a world line in space-time—the series of points across space and time that are a story unto themselves.

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[*] A term coined by Moya Bailey for the unique formation produced by misogyny and racism in combination. For more on this idea, check out Bailey's book *Misogynoir Transformed*.

Go to note reference *

[†] The film rhetoricizes this as a planet of Black men's own, but I choose to read it expansively and more equitably here. For the reference point, see: Woolf, *A Room of One's Own*.

Go to note reference †

[*] Together, speed and direction are a physical quantity known as "velocity." I will return to this idea in chapter 5.

Go to note reference *

[*] Please don't actually try pointing a laser outside of your car; lasers can be dangerous to other drivers on the road.

Go to note reference *

[*] You might find it helpful to return to the discussion about Frost's views on metaphors in physics in chapter 1.

Go to note reference *

[*] "Enby" is short for "nonbinary person."

Go to note reference *

* While writing up this section of the book, I consulted no fewer than five textbooks, and all of the ones that I expected to provide good explanations didn't. I even looked at *The Disordered Cosmos* and realized I ran into this problem the last time and decided to gloss over it. (Imagine present me shaking my fist at past me!) Eventually I turned to the book I first learned general relativity from. Robert Wald's *General Relativity* is now over forty years old. It is both widely considered to be a classic and a work that is difficult to learn from, although I loved it. (When I told my friend Joey that I learned general relativity using this book, he said, "Oh no, I'm sorry!") There, on page 66, I found the best way to think about it—a reminder that a variety of perspectives are needed when trying to understand the cosmos, and also that even for the trained professionals, it takes time.

Go to note reference *

* There's something of an involved story here about how he didn't exactly say this, but kind of said it in a book he coauthored with others, and then eventually took credit for saying it.

Go to note reference *

* It is a different equation from the famous one that says energy and matter are equivalent—$E = mc^2$—that will be described in the next chapter.

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* And for this reason, there's a good argument for saying that we should use "spacetime" instead of "space-time." In fact, in my last book, I chose "spacetime." Because, in reality, we are dealing with a different phenomenon. It is not space alone, nor is it time alone. It is a third option. For this book, I reverted to "space- time" largely out of respect for the origin of the book's title. As I discuss in chapter 5, "the edge of space-time" first appeared as a phrase in Stephen Hawking and George F. R. Ellis's *The Large Scale Structure of Space-Time*.

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CHAPTER FOUR

THE COSMIC ORIGINS OF THE 808

In which the universe begins or has always been, unclear

In the beginning, there is a mathematical catastrophe.

If we use Einstein's equation to look at the apparent beginning of our universe, there is a singularity beyond which our equations are simply incoherent. "The equation blows up" is how I might express it to a classroom of physics students, using another metaphor that we should perhaps interrogate. Trying to understand the beginning of everything involves looking at our equations that describe space- time at the exact moment when time is zero. It means realizing—in my case, with utter horror—that the math falls apart and tells us nothing about the nature of the event at that point in space-time.

In the beginning, space-time came to be ***somehow***, we rationalize. But in the beginning, there may not actually have been a beginning. Our universe might be one of an infinite number of other universes that are constantly emerging and have always been emerging. This is one version of what's known as the eternal inflation model, which builds on a phenomenon that most physicists believe occurred immediately after what I like to call "whatever came before."

In the very early moments of space-time's existence, space-time rapidly expanded. Exponentially, in fact, meaning that as space- time grew, the rate of growth also increased. The more space-time, the more it grew. Faster than the speed of light.[*] This period, what we call inflation, lasted for less than a second. When I say less than a second, I mean the inflationary era was 10^{-36} seconds long. To put that in terms that might feel a little more familiar to people who don't spend their lives with scientific notation, 10^{-36} is a compact way of writing the fraction $^{1}/1000000000000000000000000000000000000$ or decimal 0.000000000000000000000000000000000001. Most of the time we would say that this was essentially zero because it is such a small number. Nevertheless, this small, not-quite-zero amount of time matters. So what we mark as the beginning was not quite the very beginning, and nonetheless a very important moment in the history of the cosmos—key in the history of the Big Bang.

The beginning of everything can feel utterly impossible to think about and believing we can do it with just a bit of math might seem like an example of extreme human hubris. We, a smattering of atoms that are collectively experiencing something known as consciousness, think we can use equations to show that the cosmos is eternal, infinite, and multitudinous. But we know we are a product of these cosmological processes—to try to understand them is to try to understand ourselves. As the rapper Big K.R.I.T. puts it at the end of his song "Life," "*The planet Cadillactica was created within the history of the Big Bang, or what we like to call the 808.*" K.R.I.T.'s metaphor in verse reminds me, the professional cosmologist, that his album *Cadillactica* was set in motion the moment space-time and matter began to evolve in a manner that produced complex structures. Somehow within the improbability of a universe with exactly the right conditions for us to exist, not only did we come to exist but members of our community did amazing things like lay the foundations for the 808, a drum machine that is a foundational instrument to hip-hop.

The space-time that materialized in the aftermath of the Big Bang follows a set of rules that plotted a course to you, Earth, and the Southern rap from which Big K.R.I.T.'s discography emerged. I've likely never met you, but I know that you are made from hydrogen and carbon that is billions of years old. I know that the carbon was made in stars that the hydrogen formed—and that your body likely needs a smidgen of vanadium, which is made in supernovae, the explosions of stars that are chonky enough to die sudden, spectacular deaths.[*] You were created within the history of the Big Bang. This is the story, as we understand it. To develop intuition for why this account of the universe seems reasonable and even quite probable to anyone means to step outside of daily life and face the strange.

The History of the Big Bang

I once got into an argument with some people on Twitter about what the Big Bang was, and the only reason the argument came to an end is because a well-respected white-man physicist intervened by tweeting, “Chanda is right.” I think about this incident sometimes, not just because it was annoying that people weren’t respecting my hard-earned expertise on this subject, but also because the way “Big Bang” gets thrown around *can* be kind of confusing. Sometimes what people mean by it is “the point in time where space-time began.” But how could time exist without space-time?

Let’s be more precise: We often use “Big Bang” to mean the origin event of space-time. But an origin implies a place in space and time where space-time began. This is unsatisfactory for reasons that are maybe starting to be obvious to you: Space-time can’t start in space-time since space-time only exists to be a place of origin once it already exists. This calls to mind a line by Yasiin Bey, known then as Mos Def, when he guested on Common’s song “The Questions” and asked why he needs ID to get ID.[†] In the “origin event” definition of Big Bang, we need space, time, or space-time, to get space-time. This is also what people often mean when they talk about it colloquially: the broken equations at the beginning—the Big Bang singularity.

But that’s not always how physicists use the term “Big Bang” these days. Now it’s often used as a shorthand for the Big Bang cosmology, which is the collection of events that happened in the early universe. Yes: The Big Bang itself has its own history. Specifically, there’s the Beginning (whatever that was), then inflation, then the moment when the universe reheats (because it got cold during inflation) and particles start to proliferate, leading to the formation of the first atoms, which eventually form gases that become stars. At that point, we’re a few hundred thousand years in.

In my head, the stories, information, and techniques that constitute “cosmology”—the area of physics that tries to understand the universe as a whole—wrap around in loops of connected narratives. To talk about the entire universe in a singular form is almost another act of hubris, imagining that we could contain the whole thing in a single, comprehensible story. I could say that cosmology has figured out that all the universe is a stage described by a single space-time, which is expanding—just like (as discussed in the previous chapter) Friedmann predicted with his solution to Einstein’s equation and later confirmed by observations. But the thought that flickers immediately in response is how expansion happening is shaped by what's inside of space-time. The nature of the predictions we get from Friedmann's solution depends on what kind of matter and energy is in the universe and how much of it there is.

Then there is the strangeness of the particle that apparently drove inflation, the inflaton. The inflaton isn't just a particle that lives inside of space-time; it's like a wind that pushes on it, very hard, making it grow in size very rapidly. My mind conjuring that image is part of what general relativity does to a person's brain: You stop thinking of space-time as a place where things happen and instead think of a place that is happening and where that happening is shaped by what is happening "inside" of it.

This way of looking at things emphasizes space-time itself, but it's not the only perspective. We can instead try to understand the behavior of all the stuff inside of space-time. What is this stuff? Where does it come from?

Beginning to understand requires something that connects the creation of matter with whatever was there in the Beginning: a relationship between matter and energy. The link is given by what is probably the most famous equation on the planet, $E = mc^2$. This equation—where E is energy, m is mass, and c is the speed of light—says that all massive objects have a corresponding energy and suggests that mass can be converted to energy. The reverse is also true: Energy can be turned into mass, which is to say that energy can be turned into matter in the material sense. This matter-energy equivalence means that the total mass of an atom is not just the sum of the masses of its component particles but rather the sum of those masses plus the energy contained within the atom.

Special relativity teaches us that the distinction between matter and energy has limited value. The entire field of particle physics exists because of this insight about matter-energy equivalence. And so do nuclear bombs. Knowing this one piece of information transformed the human relationship to power. As the narrative caption reads at the end of Spider-Man's first comic-book appearance, "With great power comes great responsibility."[1] Understanding physics empowers us, which also means that we should make ethical choices about how we use that knowledge. One of the things I love about cosmology is that it does something very different from bombs—it inspires imaginations, creating room for more humanity.

Our Universe Cannot Kindly Pause

In Kiese Laymon's stunning novel *Long Division* about timetraveling Black kids from Mississippi, there's a memorable preteen named LaVander Peeler, who is fond of asking other boys to "kindly pause" to establish some semblance of privacy in the bathroom at school.[2] Sometimes I think about what LaVander might say if he got the chance to learn about physical cosmology. Space-time moved rapidly during inflation and continues to expand to this day. There isn't a place where motion isn't happening. You can ask the universe to kindly pause, but it can't. It was set in motion billions of years ago, and that is now its way of being.

Conceptually, what we know about cosmology can be quite rattling. When we say the universe is expanding, we mean the space-time is stretching. And we don't mean that it's expanding into anything or out of something. It's just expanding and has been for 13.8 billion years or so. When I was a teen, we were told to think of expanding space-time as galaxies racing away from each other. And certainly, this is one visible effect of what we call the "background expansion" of space-time. But what's really happening is far more fantastical than that. If you imagine that there is a ruler—the metric—measuring cosmic distances, then think about a ruler stretching more and more as time goes on. This is how physicists conceive of space-time expansion mathematically. The metric that describes the cosmos on large scales is one that changes with time, a ruler that grows, giving us a space-time that is always stretching and growing.

To visualize this, imagine a blown-up balloon with a series of dots on it, just like the one in Figure 4.1. Imagine there are squiggly lines on it too (though they are not visible in the figure below). As we fill the balloon with air, we notice that the distance between the dots expands, and the squiggly lines stretch out. This is one way to visualize the effect of the expansion of space-time on the distances between galaxies (represented by the dots) and on the wavelength or color of light (represented by the squiggly lines). We call this a "background" expansion because, though broadly speaking expansion is happening, local gravitational pull holds the galaxies together. The galaxies are full of stars, dust, and dark matter (more on that later), all held together by gravity. This means that in a general relativistic picture, gravity is now capable of doing two things: holding stuff together—and pulling the cosmos apart.

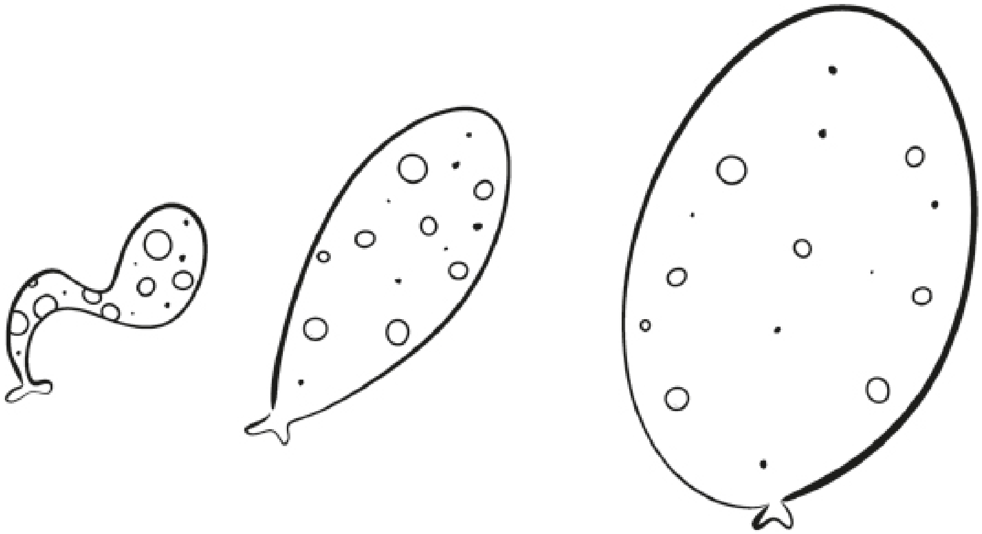

Figure 4.1. On the left, you see a balloon that has not been inflated, covered in dots. As the balloon is inflated (middle and right), the dots get farther and farther away from each other. This is a decent visual metaphor for space-time's expansion and how it creates distance between galaxies.

Space-time's expansion may be shocking enough, but now imagine the possibility that the expansion rate can change, and rapidly. This is the gist of inflation.

Inflation was conceived in response to a big-picture question. As a postdoctoral fellow, Dr. Alan Guth was curious about how to explain what Hermann Bondi called the Copernican principle: the idea that there is no special location in space-time, and that the universe looks about the same in every direction, from every location. This idea seems simple enough until you consider that the speed of light is finite, and that light doesn't travel instantaneously but rather takes time to move from location to location (think back to the light cone in Figure 3.1). Even light from the sun takes time to arrive at the Earth—we cannot see changes there until the information has traveled for the eight minutes light takes to get here. On cosmological scales, this means that at some point the universe can be so large that it will have been a long, long while since different parts of space-time have been in contact with one another, inside each other's light cones, if ever. So how could the universe possibly look the same in every direction, from every location, after such a long period?

Guth suggested that there was an era of rapid expansion in the early universe, when space-time became huge in just a fraction of a second. This inflation would mean that places previously in close contact with one another were suddenly spread far apart—but all with the same information. What happened in this split second is called cosmic inflation, summarized beautifully in GZA's song "The Spark": "Small enough to fit in your hand, a nanosecond later / It was the size of Mars and becoming greater."

The rapid, inflationary expansion of space-time helps explain why space-time appears to be both homogeneous (the same everywhere) and isotropic (the same in every direction), despite the finite speed of light limiting contact distances and times. The universe looks roughly the same everywhere we look (homogeneous) and in every direction we look (isotropic): Galaxies and groups of galaxies are randomly distributed, but there's no direction that looks special. Why? Inflation solves this problem by making space-time expand so rapidly that regions that are now distant and have no way of being in causal contact with each other at the present time could have been neighbors in the past. This is how regions that can't communicate with each other because a light signal would never connect one to the other *now* "know" to look similar.

Inflation also helps provide an explanation for where everything comes from. The inflaton is a particle that starts out with a lot of "potential energy," which is the amount of unused energy something has available to spend (think of it like a savings account). This potential energy actually fuels the inflationary expansion of space-time. As the cosmological timeline moves forward, the inflaton converts its potential energy into kinetic energy—the kind of energy that's associated with motion and the expenditure of energy. This conversion of potential energy into kinetic energy is what creates all the energetic particles that we ultimately are made of. As Guth put it in his own book about the subject—which I recommend—"In the context of inflationary cosmology, it is fair to say the universe is the ultimate free lunch."[3]

Guth's point is that inflation is the beginning of everything: every particle we've seen and every particle we think might be out there. You've heard of an electron, but maybe you've never heard of a quark. Quarks are, like electrons, subatomic particles. There are six kinds of quarks: up and down, top and bottom (also known as truth and beauty), charm and strange. And particles you've heard of are made of them: The neutron and proton are each made of three quarks. The neutron is made of one up and two downs, and the proton is made of one down and two ups. The shared building blocks mean that neutrons can turn into protons—I'll return to this later! For now, I just want to make the point that the inflaton is one of the reasons we—quark and electron assemblies—are possible at all. We think we are a product of energy sloshing around in space-time, but this is an active area of research where we are still trying to work out the details.[*]

Visible matter isn't the only matter that may have become energetically possible due to the inflaton. We also know that dark matter is almost certainly out there, invisibly dominating the evolution of galaxies and clusters of galaxies. Dark matter is not visible matter, and it is by definition not accounted for in the standard model of particle physics. One might think this is an easy problem to solve because it is simply a matter of growing our particle menagerie, adding a new type of matter to the list. We know for sure that dark matter is a particle we've never touched or seen—and we know it outnumbers visible matter at a rate of about 5 to 1. Which is to say, it's most of the matter in the universe. Dark matter should really be called invisible matter: We have so far been unable to look directly at it, even though we can see its impact on visible matter. Trying to understand dark matter's material qualities is quite the challenge—an entertaining one for dark-matter scientists like me (you'll hear more about this in chapter 13). The one thing we know is that like visible matter, its cosmic evolution was shaped by the aftermath of inflation.

In other words, inflation is an extraordinary model with far- reaching implications for the history of space-time and everything inside of it. Inflation was such an astonishing idea that Guth was immediately offered a professorship with tenure at his alma mater, MIT—leapfrogging over what is for most people a long six-to-sevenyear process.[*] As a classic example of how science is a dialectic process, Guth's concept was quite interesting, but the way he implemented it turned out to be dysfunctional. Other scientists came along to contribute their own narratives of how inflation occurred.

The fact of cosmic inflation invites the question of what set space-time off: Why would it go racing like that? The equations that describe inflation suggest to us that in fact inflation can happen eternally, forming new bubbles of space-time endlessly. It's a multiverse, and we just live in one corner of it. We are here on Earth, using specialty quantum eyes—telescopes—to watch space-time expand. We are watching the expansion accelerate too (more on that later). Space- time is a place that has happened and is happening.

The Edges of Space-Time

There is still the question of why it is happening—and whether we should care. I think the reason we should is spelled out beautifully in Tracy K. Smith's poem "The Universe Is a House Party," where we are invited to consider the links between an expanding universe and the mundane: "The universe is expanding. Look: postcards / And panties, bottles with lipstick on the rim."[4] Part of what makes this juxtaposition work, emotionally, is the repositioning of our everyday lives as part of a greater, billions-of-years-old story. Smith's poem illuminates how the mundane is also the cosmic and becomes a new way to access the question of what it means to do cosmology. When we ask *why* space-time happened, or *how,* we are asking about what led up to the cup of tea sitting on my desk, or the socks you put on this morning.

We don't know. In the beginning, you'll recall, there is a mathematical catastrophe that we must contend with. Which is to say that we cosmologists, the experts on the origin and evolution of space-time, are unsure exactly what happened at the beginning, and whether there even was a "what" that happened at all. Our metaphors, our stories, end abruptly: We reach the edge of our understanding. And we can't explain why the story exists if we aren't even sure how it starts.

I realize this is unsettling. The public is told over and over that scientists, perhaps especially physicists, are authority figures who know what we are talking about. And there's a lot that I do know, including what questions we have about the stuff we still don't understand. The practice of science isn't about what we know, though. It's about what we don't know. If we knew everything, there'd be little science left to do, and frankly this book wouldn't need to exist. There'd be no tantalizing questions about space-time for you, the reader, to ponder. Our ignorance is, in some sense, a cosmic good. At least, it's a human good. To figure out *why* means to live at the margins of our understanding.

And it is not like we know nothing. I can tell you with complete confidence that there is no center of the universe, even though some of us might imagine ourselves to be exactly that. Instead, we are on the third planet out from a very mid yellow star in the arm of a relatively typical spiral galaxy that lives inside what we expect is a very normal dark-matter halo—one of billions of galaxies in the observable universe. Possibly, there are a lot of us out there in the cosmos, traveling on what are effectively permanently isolated islands (barring some major technological advances in human manipulation of space-time).

While the observable universe has no center, it does have edges beyond which we cannot see. Before you read my explanation of what I mean, questions I want you to ask about this statement include: Beyond which we can't see the past? Or beyond which we cannot send signals to the future? I'm not talking about time travel in the science-fiction sense, but the idea that it takes light time to travel and this creates boundaries.

The space-time boundary that has made its way into popular culture is the event horizon of a black hole, widely understood as a point of no return for all things. In cosmology, we run into a similar phenomenon. Thinking about this takes a little bit of patience because of the expansion of space-time. Imagine a scenario in which you have a very long measuring tape. At any given moment across all of space- time, the measuring tape could measure a distance between a galaxy far away from our own and Earth. Notice that light is how we access information about the status of the measuring tape. Recall that due to its finite speed, light takes time to travel from one point to another. This means that the information about the status of the origin point of the tape (the galaxy that is far, far away) would take time to get to us. By the time we see a signal from that galaxy, telling us how long the tape is, the tape would have been stretched longer than its earlier size because space-time would have expanded—the distance would grow while we were taking the measurement. Because the distance this light must travel is growing, and light can't speed up (by definition, it's the fastest thing there is), there is a boundary: a maximum distance something can be and still have its light reach us eventually. This is the particle horizon, and it is the edge of the observable universe.

The particle horizon is an edge defined by the age of the universe and the universe's rate of expansion. The point where we start our measurement matters. If we are beginning at the start of space-time, then we are thinking about the entire observable universe. But instead, we might be interested in our ability to see a light signal that is being emitted right now, rather than from the past. This points us to another possible edge: a cosmic event horizon. These are defined by distances from which a signal will never arrive to us, no matter how long light travels. Take two particles: If they are separated by a large enough distance, that means they are unable to communicate with each other now, even if they could in the past. It turns out that the universe itself has impenetrable boundaries.

But I want to caution you against always imagining this in familiar material terms. If you're a *Star Trek* fan, something that might come to mind is the galactic barrier, a concept that was first invoked in one of the greatest episodes of *Trek* ever made, "Where No Man Has Gone Before." The third episode of the original series and the pilot that got *Star Trek* greenlit, this episode is a meditation on what happens when an individual person is endowed with almost unimaginable power to make things happen simply by wanting them to. How is this power acquired? According to the writers: by going through the galactic barrier, of course. I hate the galactic barrier, a bad plot device that has no real-world counterpart.[*] The idea behind it is that there's a special band around the edges of the galaxy that prevents "signals" from coming through. This is preposterous, since we see light from other galaxies all the time—I plan to capture some tonight when I take my telescope outside. And professionals and amateurs were already doing this well before 1966, when the episode was made.

In "Where No Man Has Gone Before," the galactic barrier is a physical boundary that exists at a specific point in space at all times. But particle horizons and cosmic event horizons are defined by the relative locations of two objects at a given time: The particle horizon is the maximum distance light could travel to an observer in the time that the universe has existed, and the cosmic event horizon is the location beyond which distant light can never originate and subsequently complete a journey to us. Different people will see different horizons, depending on their location in space-time. These space- time-dependent horizons challenge our notion of boundaries as fixed phenomena that exist independently of what they contain.

Our Cosmological Existence

Hopefully it's clear to you by now that cosmology is many things. Cosmology is a collection of information. Cosmology is also the story of us, and it is so compelling that every human community has one. Like Big K.R.I.T. points out with his album *Cadillactica,* even a comprehensive history of hip-hop and the 808 necessarily begins with the Big Bang.

It makes sense that we'd wonder about how we are possible. Explaining the fact that we—and the 808—exist at all is a physics problem. Change the properties of the electron or some other fundamental number just a little bit, and we could never come to be, or as in Koji Suzuki's novel *Edge,* our physical makeup destabilizes and disappears. Our existence is the product of an elaborate series of cosmic events. You may have heard Carl Sagan's quip, "We are made of star stuff."[5] But think about all the fail points that precede star formation. Tweak the laws of physics even a little, and structure formation, the creation of stars and galaxies and dust and everything else we can see, perhaps never occurs—at least, not in a way that makes our existence as likely as it is.

Just how likely are we? That's a hard question to answer. One way to get out of worrying about any of this is to believe that there is a multiverse—many universes—and we just happen to be in the one where the properties were just right for our existence. This multiverse is, in fact, one possible consequence of the eternal inflation I mentioned earlier. There are physicists —including some of my best friends!—who believe this. I find their viewpoint frustrating. I find the fact that their viewpoint is rather popular even more frustrating. In my opinion, they are wrong. This solution never requires us to come up with a substantive, in-universe explanation for why our universe has the properties that it does, and I don't think we should be so ready to give up on that possibility. These multiverse ideas are also hard to test, which raises fundamental questions about whether we are still in scientific territory and what exactly physics is (more on this in chapter 16).

There is a lot we know about cosmology, but there are still things that we don't know. That's the challenge and beauty of doing this kind of work, here in a corner of the universe full of sentient, sciencing beings. There is a kind of freedom in attempting to understand the logics of the universe. I remember that we African-descended peoples in the Americas have received the concept of Sankofa as a gift handed down from one generation to the next, despite living through some of the worst conditions in human history. Sankofa teaches us to go back and get our history—cosmology included.

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* This is true but can also be confusing. No rules are being violated. The speed of light is a limit for phenomena traveling *within* space-time, not on space-time itself. Is the speed of space-time especially useful to think about? Maybe not. But here I just want you to have a sense that space-time's expansion was like a bat out of hell—in a hurry!

Go to note reference *

* Scientists are still unsure of what exactly the body uses vanadium for, but insulin regulation seems to be a popular explanation. This isn't my area of research, so of course consult with a doctor before you go chase down a vanadium supplement.

Go to note reference *

† I just want to thank Nick here, for quoting this to me about a bajillion times when we were in grad school.

Go to note reference †

* I write about my own work in this area in my first book, *The Disordered Cosmos.* (See chapter 4, "The Biggest Picture There Is.")

Go to note reference *

* And in the process, Alan—as I know my former postdoc advisor—became a widely respected teacher and mentor. Not only has he been a champion for me but he has also taught and mentored many of the women (and some of the men, like David Kaiser!) who have mentored me throughout my career. Alan is a beloved figure in the community, not only for his brilliance but also for his kindness.

Go to note reference *

* My dislike of the galactic barrier is so notorious among my *Trek* crew that my friend Barry Rice, a fellow astronomy professor, makes an effort to bring it up whenever the opportunity presents itself. Barry's behavior has not been a barrier to our friendship, somehow. I also discussed it with the amazing astrophysicist and *Trek* science advisor Dr. Erin Macdonald on the June 19, 2023, episode of NPR's *Short Wave.*

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CHAPTER FIVE

BEYOND A COSMIC BOUNDARY

In which we learn that boundaries are central to physics

> The greatness of the great batsman is not so much in his own skill as that he sets in motion all the immense possibilities that are contained in the game as structurally organized.
>
> —C.L.R. James, *Beyond a Boundary*[1]

What Do They Know of Physics Who Only Know Physics?

To do cosmology, to do the work of a physicist, is to try at all times to be as clever and creative as possible while understanding that actually most of the time, you will not be. The fact that we try to be creative does not mean our work is without ground rules. Like the batter in cricket—a game my Trinidadian grandfather C.L.R. James would have hated to hear me claim is similar to baseball—physicists work within a set of rules, a set of boundaries. These confine our game, as it were, but they also advance it by giving it a sense of direction. The boundaries help us keep track of what we know and *how* we know. They are part of what makes the work of a physicist possible.

Regarding the cricket batter, Nello (as my grandfather was known to family) continued: "Cricket, of course, does not allow that representation or suggestion of specific relations as can be done by a play or even by ballet and dance. The players are always players trafficking in the elemental human activities . . ." This is also the case for physicists, whose elemental human activities include sorting through what is relevant and when, and expressing curiosity about what options remain when we have finally uncovered some new rules of the cosmic game.

There is a tendency to portray the work of physics as a series of experimental quandaries where theory chases new experimental results, but this isn't always true. While it's true that experiment has been a wonderful motivator, physicists are sometimes led by the equations in front of them. For example, James Clerk Maxwell hypothesized the connection between the theoretical notion of electromagnetism and the visible phenomenon of light more than a decade before there was any experimental proof that the physical expression of electromagnetism was, in fact, light. He didn't have definitive proof, but when he looked at the equations, he saw the possibility. Various elements of research on the quantum nature of our cosmos have also worked this way, and in fact the history of quantum mechanics is a beautiful example of a tug-of-war between theory and experiment—noticing, guessing, data, all working together in a loop. It's beautiful and messy and often, in hindsight, not very smart while occasionally being some of the most brilliant things humans have ever done.

This work of hypothesis is a key feature of doing science—both for a theorist and an experimentalist. People doing the work of physics didn't always agree on this. The eighteenth-century French physicist and mathematician Gabrielle Émilie Le Tonnelier de Breteuil, Marquise du Châtelet, popularly known as Émilie du Châtelet, felt compelled to make a forceful argument for the importance of hypotheses. In her work of natural philosophy, *Foundations of Physics,* du Châtelet wrote that hypotheses "are as necessary as the scaffolding in a house being built; it is true that, when the building is completed, the scaffolding becomes useless, but it could not have been erected without it."[2] In this metaphor, when we have a successful model—the completed house—we mostly notice the finished product, not the scaffolding underneath. But of course, the scaffolding is what establishes the strength of the finished product: whether it works, whether it holds together, and the boundaries of that success.

Physicists are professional boundary-pushers. I was not taught to see science this way, but arrived at it when reading the late José Esteban Muñoz's *Cruising Utopia: The Then and There of Queer Futurity*. There, with Muñoz's work on the utopian theory of cruising (for sex in gay bars, among other things), I understood him to be saying that queerness lives at the boundary of what we think we know about the potential configurations of human desire and thus the social potential within us. I remember the *aha!* moment, realizing that in this sense, science is quite queer, especially at the boundaries. For a queer person like me, science was in fact a natural environment, since the work of a scientist is living at the boundary of what is known and unknown and trying to push that boundary forward as much as we can. That process involves continuous contestations and competing interpretations of what the truth is.

Boundary-pushing is, of course, not confined to that which is identifiably queer or scientific. Think back to Lewis Carroll's Victorian classics *Alice's Adventures in Wonderland* and *Through the Looking-Glass,* two books that take the world as we know it and both flip it and reverse it. The best film adaptation of these stories is the 1933 Norman Z. McLeod film *Alice in Wonderland,* which merges the two books.[*] In McLeod's *Alice,* the action begins when Alice does something rather cheeky: Convinced that the mirror hanging over the mantel contains a mirror universe, she climbs on a chair and looks over the edge of her world to inspect the edge of the reflection world on the other side. Eventually, she climbs up on the mantel of her living-room fireplace and steps through.

In the lead role, Charlotte Henry gives us a bold and confident preteen girl in a poofy dress who is bored with the world she knows and acutely aware that there is more to the universe than what her upper- class Victorian life appears to offer. She questions the boundaries of her own space-time and in the process ends up in a completely different one. Alice had ideal conditions for her curiosity—even in the book, where she first ends up in Wonderland not by going through the looking glass (that's what happens in the sequel) but instead by following a strange rabbit down what she initially believes to be a rabbit hole.

Alice, the character, represented her own kind of boundary transgressions. When he created her, Carroll was a mathematics don—the 1860s equivalent of a professor—at Oxford University, an institution that is both famous for its researchers' incredible contributions to science as well as one of the single largest beneficiaries from violently racist colonialism and enslavement. At the time, there were no woman professors in the UK, and Oxford did not award degrees to women. Across the Atlantic, the United

States was embroiled in a civil war that was largely about the Confederacy's desire to keep nearly all the Black people in the country enslaved. In other words, Alice existed as a kind of mythological creature of her own time, an idealized observer unfettered by the boundaries produced by sexism, the worries of surviving under capitalism and war, or the literal boundaries of space-time.

Even in the imagining of Alice, however, Carroll maintained certain boundaries. Alice is a white girl, of upper-middle-class status. I never could have been that Alice in 1865 when *Alice* was first published. Nor could my mother, Margaret Prescod, or any of our shared ancestors. The American Civil War had just ended, and while our ancestral land of Barbados had technically been liberated from enslavement in 1838, almost a century would pass before any Black Bajan children, especially little girls, had access to education, much less a home like the Big House where my mom sometimes accompanied her father to beg for food. Barbados was still a disenfranchised British colony until 1966. Alice's embodied history exists along racial, class, and colonial boundaries that I was born on the wrong side of. And it would be easy to say that someone like me could never see herself in Alice, because of the social boundaries that are constructed around her historical identity and my own. Yet there is something in her that feels universal and familiar: that curiosity and belief that the world is bigger than what is immediately happening around us; bigger than the bad things that are happening to us, as my mom once put it to me. I think each of us can remember a moment when we looked deeply, hoping to see over the edge of what we know about space-time.

Questions of space and time are not only metaphysical in the cosmic sense. For those of us who have had to sort out being the one to queer things (intentionally or not), they are also sites of personal urgency and curiosity. As Sara Ahmed writes in the book *Queer Phenomenology,* which investigates the spatial phenomena that define queer experience, "If orientation is a matter of how we reside in space, then sexual orientation might also be a matter of residence; of how we inhabit spaces as well as 'who' or 'what' we inhabit spaces with."[*] If we look at our communities, we see evidence that people all around us are creatively questioning how the universe works, learning to manipulate its material manifestation, and doing so in ways that are not only peaceful but also beautiful.

I see this especially in Black cultural work, which has always made sure that Black children hear many stories of people looking for the boundary of what is possible and pushing past it. Earlier I wrote about rapper Big K.R.I.T.'s bold allegory that compares the birth of Southern hip-hop with the Big Bang itself. Those lines appear on the album *Cadillactica,* which also includes its own story of technoscientific curiosity in the opening verse of "My Sub Pt. 3 (Big Bang)." There, Big K.R.I.T. narrates the beginning of car sound-system modifications to blast rap music:

This is how it all started way back
First the boomin' voice then the bass crack, 808
And that's when we first started fire

The lyrics go on to describe a bad wiring situation for a set of speakers in a car, causing the fire. Eventually the (amateur) electrical engineer setting the system up moves the speakers into the trunk, solving the problem. This is a story that meaningfully links Black Southern crunk to the Big Bang, recognizing that crunk is also a reflection of the cosmos and all its possibilities. Importantly, K.R.I.T.'s intrepid inventor gets knocked over and has to get back up and brush his shoulders off—to learn how to build the system in the right environment so that it has what we in theoretical physics would call the right boundary conditions. Anyone who has messed with an electrical system in any serious way knows that you have to send excess electricity somewhere, in a process called grounding. The ground becomes a boundary that sustains the working of the electrical system.

I can only take a theorist's perspective on this, because frankly you do not want me in your lab, breaking your equipment. Trust me, this is a boundary that should be maintained. When I think about what's involved in figuring out how to put giant speakers in a car (don't ask, I don't know how), I think about the experimentalist figuring out how to manifest a specific solution to the equations that govern electricity and magnetism. And that means taking those general equations and figuring out how to solve them in the very specific conditions our problem exists in—for example, the strength of the available power supply and the physical extent of the trunk. This is what we call a boundary-value problem. It is the problem Schwarzschild also needed to solve to find his black-hole solution, and the same problem Friedmann solved, proving an expanding space-time is possible. Boundaries create challenges, but they also create possibilities.

Boundary Work

Historically, physicists come in two categories: experimentalist and theorist. These days, the boundary between these groups has become quite blurry, especially with the advent of computation—work that focuses on making predictions with computers and code. People doing research with computational tools are sometimes actively engaged in experiment and sometimes in theoretical work where they are developing and solving equations that describe physical scenarios. This is the traditional work of a theoretical physicist: create models of physical systems and solve mathematical equations that describe them. Though nearly everyone does some form of computation, and my own research group is best known for our computational work, I am happiest when I am cruising through a calculation by hand with a 0.7 mm Pilot G2 gel pen on nice, smooth paper. The moment when the pieces come together is a deeply satisfying mental click. No matter what I do, I will always be this kind of theorist: pen and paper.

To solve an equation, it is not enough to write down the correct equation, whether one does this by handwriting or typing. We also need information about the specific conditions that our physical system is experiencing, or the conditions that are natural to the physical system itself. As an example, we want to understand how the presence of dark matter affects the rate at which space-time is expanding, even if we are unsure what dark matter is. In physics, these types of inputs restrict how space-time can behave by imposing some guidelines on which solutions to our equations can be considered—we can only consider solutions that assume the presence of dark matter, because that's the universe we actually live in.

The practice of theoretical physics is all about these kinds of restrictions, or what are more frequently called boundary conditions. Socially, we know boundaries are important. Any psychologist will tell you that they are essential for healthy social experiences between humans. But we also have a physical sense of boundaries that goes beyond social interactions. We can think of the ground as a boundary we are familiar with—the boundary between the solid part of the Earth and the atmosphere, which has several layers, including the one that we simply experience as the air that we breathe. If I want to solve a problem that involves the size of the Earth, I have to think about what boundaries to set to establish what counts as "the Earth" for the problem. Most of the time, I won't care about the atmosphere —which is complicated anyway and doesn't have simple boundaries the way the surface does—so I will establish that the boundary for my problem is the Earth's surface.

Now, let's say I want to solve a problem that involves the difference between the pressure close to the Earth's core and the pressure at the surface of the Earth in a location at sea level. These pressures are the boundary values (or, alternatively, boundary conditions): One edge of the problem is the position near the core; another edge of the problem is the surface. To solve the problem of the difference in the value of pressure, I potentially need to know the value of the pressure at both locations.

Boundary conditions are everywhere. Look at what page you're on. Now close the book and look at the image in the center of the cover. If you looked, you noticed that there is a circular-like image but with two dramatically different halves—with a firm boundary running down the center, creating an edge to each side. If we were modeling the image and wanted to know when to transition from the black- and-white pattern to a neon rainbow, the information that specifies where that edge is on the page is the boundary condition. It is a rule that each half of the circle follows.

Knowing how to calculate in theoretical physics means knowing how to solve boundary-value problems. We need to understand the conditions of a system at the boundary in order to fully understand the possible evolution of the entire system. There are different kinds of boundaries that we might be taking into account. One example is called an initial condition. In this case, we are using the conditions at the beginning point—either in space or time—as the boundary information that we know. This helps us do important calculations, like calculate how a baseball moved when Jackie Robinson hit a home run. If I want to calculate how far the ball will go before it hits the ground, I need to know the initial speed when it leaves the pitcher's hand, and I need to know how fast the bat was going and at what angle. That won't give me quite the correct answer, because it would also be helpful to know how fast the ball was spinning and in what direction. These are the initial value conditions, the beginning conditions. With all this information, there's a very simple equation that anyone with a bit of algebra can use to calculate how far "outta there" Robinson sent the baseball. It's perhaps strange to think of something like an initial condition in the context of boundaries, because we tend to think of boundaries as existing in space. It is normal for physicists to distinguish between these "initial value conditions" and "boundary conditions," but I think this is largely a distinction without a difference.

The examples I gave above can be fit into a larger theoretical framework, something that in academic spaces is more the purview of philosophers than physicists. In her work, philosopher Julia R. S. Bursten explains that boundary conditions have several possible roles in physics. One is to "specify the scope of a model."[3] In other words, they can ensure that a model can be used to describe a physical scenario by preventing the model from being overly broad. As an example, when I say, "I enjoy store-bought ice cream," in actuality I only mean "I love Häagen-Dazs." This preference is an increasingly costly boundary condition on our household grocery shopping.

Boundary conditions are both abstract and practical simultaneously. Philosopher Dániel Paksi gives a relatively simple historical example that helps to illuminate the abstract role that boundary conditions play in not just calculating but actually conducting experiments. There he recalls experiments run by Galileo Galilei, who spent a lot of time rolling balls down inclines like the setup illustrated in Figure 5.1.

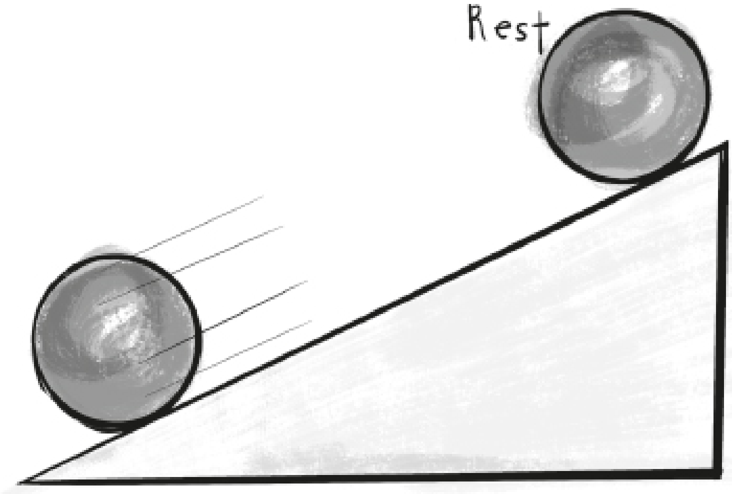

Figure 5.1. Galileo saw mystery in the simple act of rolling a ball down an incline. The ball starts out at rest at the top, and he wondered how to describe what happened when he let go.

As he notes, Galileo wanted to understand whether there was a correlation between weight and acceleration.[*] One immediate question that someone could ask about his experiments is whether the angle of the incline matters—that is, how sharp the drop from top to bottom is. Galileo didn't think that the angle would affect the correlation between weight and acceleration, so he chose the angle—which determines the height of the wedge—according to other experimental considerations. Paksi points out that this choice was an example of enforcing a boundary condition, using a structure to support the extraction of important information. He calls these "conceptual and instrumental tools . . . to reveal the deeper physical reality of nature."[4]

What we can learn here is that physics is not just a collection of information, like the correlation between weight and acceleration—it is also the practice of careful, informed abstraction. Boundary conditions are so important that a foundational text in theoretical physics names it as one of the two major areas of "discussion of the universe." Stephen Hawking and George F. R. Ellis open their 1973 book *The Large Scale Structure of Space-Time* with this observation:

> The view of physics that is most generally accepted at the moment is that one can divide the discussion of the universe into two parts. First, there is the question of the local laws satisfied by various

> physical fields. These are usually expressed in the form of differential equations. Secondly, there is the problem of the boundary conditions for these equations, and the global nature of their solutions. This involves thinking about *the edge of space-time* in some sense.[5]

The italics are mine, there in case you forgot the title of the book you're reading. There's a lot of "technobabble" in this quote, so let me situate it in context. First of all, what they said is the same thing I told you before: Theoretical physics, and in particular theoretical cosmology, is a series of boundary-value problems. Hawking and Ellis's was one of the first books to attempt to write down everything that humans knew about mathematical cosmology. They were specifically focused on establishing the physics of black holes and the Big Bang moment. The claim that they make is that (theoretical) physics could be entirely understood as a process of solving a specific type of mathematical equation—a differential equation. In fact, they were specifically focused on one particular differential equation: Einstein's equation. This is a point of such significance that I named this book after a line from their opening paragraph.

Formally, a differential equation is a mathematical formula that relates a quantity to how that quantity changes. In physics, we are particularly interested in differential equations that give us what is known as an equation of motion for a system—the equation that, for example, tells you where a ball is after a cricket batter hits it. Let me use a metaphor—and an equation you've probably seen before—to provide insight into why differential equations are so important.

Start with this fact: Every equation has two sides, with an equals sign = in the middle.

In the case of the differential equation, at least one side involves a quantity that is changing—over time, or over space (and yes, as we get more advanced, over space-time). Speed is an example of a quantity that represents something changing with time: Speed is the rate at which an object's location is changing with time. Speed is also something that can change with time: If you increase the speed of your bike, you accelerate. If you slow down, you decelerate.

A differential equation is a set of rules that these changes have to follow. And you've probably heard of at least one before, the most famous differential equation in the world, also known as Newton's second law: $F = m \times a$, which says force (F) equals mass (m) times acceleration (a). I just told you that acceleration is the change over time of speed, which again is the change in location over time. So the a in $F = m \times a$ represents change. Put simply, if I know the value of the force and how massive an object is, this equation tells me how I can calculate the acceleration. This is a real scenario: Sometimes we know the force, but we don't know the acceleration.

The formula has the power to go in the other direction too. It tells me that if I want to know the force, all I need to calculate it is the mass and how the speed is changing with time, its acceleration. While this is helpful, usually what I want to know is the location—and how that is changing with time. We want to know how a force affects *where* something is and *when* it is in that location. In other words, I want to know how force is creating motion and position in space. Newton's second law is a differential equation that helps us get there by giving us the acceleration when we know the force and mass.

If we know the acceleration, we have almost everything we need to compute the location. *Almost.*

What we are missing are the boundary conditions, or the initial conditions. Even if we know the formula for F, if we want to use it to calculate information about position over time, we need more information. This is because the acceleration tells us how velocity—the thing that quantifies speed and the direction of that speed—changes over time.[*] But we can't use that information to calculate the velocity unless we know its value at a specific moment in time. Similarly, once we know the velocity, we can't use that information to calculate position unless we know something about the position at a specific moment in time. We don't need to know this information at all times, but we need to know it at least once. For example, maybe you're in a bike race, and at the starting line—which we will now call the origin—you assign the value of 0 to your location, and also you're not moving, so your speed is 0. This is easy. Those are initial conditions—your conditions at the beginning of your activity.

So the claim Hawking and Ellis made—and that I am now making to you—is that theoretical physics is a series of more elaborate versions of this boundary problem. You have a formula that tells you how things change with time, space, or both. Given a couple of bits of information about how those things behave initially or at some physical boundary, you can come up with a solution to the formula that allows you to describe what is happening, what has happened, and what will happen. It's that simple, in principle, at least in the deterministic world of Newtonian physics, though the equation can sometimes be difficult or impossible to solve.

Boundaries are evidently valuable. But we sometimes strain against them. We want to know what's inside a black hole and whether the universe can have an edge—if it has an edge, how do we think about what's beyond that boundary? If the universe is unbounded, does that mean there is nothing beyond it? We need boundaries, but we also struggle with what they may be telling us.

Symmetry and Freedom

When faced with an equation that is difficult to solve, the first thing we do is look for ways to make it easier, obviously. Friedmann and Schwarzschild both did this with Einstein's equation, yielding historically significant solutions, using something called symmetry. You might associate the idea of symmetry with ideas about art and beauty. In fact, the parts of *Beyond a Boundary* that I quoted earlier are from the chapter "What Is Art?" In it, Nello argues that cricket is art, using the discussion as a starting point for a general treatise on aesthetics and the nature of beauty. While this seems far afield from the work of physics, within our professional community, particle physicists are rather notorious for being easily seduced by beauty because of symmetry. Symmetry, generically, is a property that a physical system has and which does not change even when certain conditions change. For example, if I run time in the backward direction and nothing changes, then the system obeys time-reversal symmetry. Symmetries are beautiful because they are simplifying and also fascinating.

It's one thing to hear this as an abstract idea, but a concrete example might help you better understand. Look at these lines from Missy Elliott's song "Work It":

I put my thing down, flip it and reverse it
Ti esrever dna ti pilf, nwod gniht ym tup i

This is one of those things that causes a special *aha!* moment when people realize that the second line is the first one in reverse order. "All those years of thinking she was just talking some creative gibberish," people find themselves saying. First of all, we should all know better than to assume anything but *levels* to Missy Elliott's genius. The story, as it has been explained in the press, is that a sound engineer played the clip backward and Missy Elliott said yeah, let's keep it. But even if you're told that these two lines have a time-reversal symmetry—the second line playing backward in time sounds exactly like the first line going forward in time—it's hard to hear it. So I invite you to do what I did: record the sound from the music video into your phone, download an app that plays audio in reverse order, and listen to it for yourself.

While "Work It" has lines that display time-reversal symmetry, the entire song is not written that way—you couldn't play it backward in time and have it sound the same as it does playing forward. This is an asymmetry. And such asymmetries exist in the universe. While someone could maybe figure out a way to reverse-engineer a Jackie Robinson home run (maybe not, since Nello said that's art!), no one can turn back time, no matter how many times Cher opines about wanting to. The arrow of time always seems to go forward. The question of *why* it might be like this is something we will return to later in the book.

Symmetries are not, generally speaking, boundary conditions. But they are properties of a physical system that can govern its possible behaviors, and in that sense, they place sometimes helpful bounds on equations by reducing the number of features we have to consider. To impose a symmetry means the thing has to be symmetrical in the way described.

Although you met special relativity through the lens of a finite speed of light and the implications this has for relative motion, I could also have introduced it to you as a theory that imposes a specific type of symmetry on space-time known as Lorentz invariance. This symmetry is one that you are already familiar with: The laws of physics are the same for every observer that is moving in an inertial frame. To give you a sense of why this counts as a symmetry, let's look at the example of the Sankofa adinkra, shown in Figure 5.2.

Figure 5.2. The top of the curve on the left is the same as the top of the curve on the right, if it was flipped to face the other way. This is a reflection symmetry, also known as a mirror-image symmetry—when the object undergoes reflection, it looks the same.

Fundamentally, symmetries are about a system not changing, even if the conditions are altered. In the case of the Sankofa adinkra, the condition that might create change is the reflection. But the adinkra does not vary under reflection—it is invariant. Thus, more broadly, the principle of relativity and Lorentz invariance represent a symmetry. "Invariance" means to not vary; to not change. The laws of physics do not vary with the observer; the laws of physics are the same for every observer. I've always been a fan of what this implies—that given the same conditions, equipment, and inclination, any person could take the same measurements, even if we varied in our creative interpretations of the meaning and significance of the results. Symmetries like these help us bound a problem and its possible solutions.

Returning to the expanding universe and black-hole solutions found by Friedmann and Schwarzschild, they both used something called spherical symmetry. This symmetry imposes the rule that everything has to look the same even if you rotate it, no matter what direction you rotate it in. Friedmann's solution also assumes the Copernican principle is correct, that the universe is homogeneous and isotropic on the largest scales. When I mentioned that idea in the last chapter, I didn't say it had anything to do with symmetries. But the universe looking the same no matter what direction we look in or what part we look at is a symmetrizing assumption that simplifies the equations a lot.

Symmetries can open doors. Mathematician Emmy Noether showed in the early twentieth century that the presence of certain types of symmetries arising in mathematical formulations of physical theories corresponded to conservation of observable physical phenomena like energy. Using Noether's theorem, we can make important connections. For instance, the theorem shows that there is a direct link between time-translation invariance—a symmetry of a system where the physics stays the same even if we change when we start measuring our time interval—and conservation of energy. Absolute time isn't itself observable (or real, as you now know), but conservation of energy is directly observable. As a Jewish woman in early 1900s Germany, Noether ran into all kinds of social boundaries, yet her observation turned out to be one of the most important in all of twentieth-century physics. It helped provide insight into general relativity and eventually aided in the discovery and understanding of fundamental properties of particle physics.

Beyond Our Boundaries

Boundaries are often a good thing, but there are scenarios in which they are not. National and political borders are fictitious boundaries in the sense that they are political constructs and can change. But they are also very real, because political constructs have material consequences, like when people trying to cross into the United States at the southern border face walls, dangerous rivers, violent border agents, and weaponized barriers that can kill. On one side of that border there is a mass of land governed by the political construct known as the United States; on the other is land governed by the political construct known as México. We all live within the enclosed boundaries of some kind of country, though some of us live in places where the boundaries shift with some frequency or are regularly violently contested. There is real physical, political, and social signifi-cance to being enclosed within one set of borders or another.

Boundaries can also provide information about what can happen inside of them. This is true not only with political boundaries but also with physical ones. Thus, we can have one equation that generically applies to calculating some information but has a different solution depending on what boundaries we are respecting when we solve the equation. Establishing a careful and clear understanding of boundaries and information about what is happening at those boundaries is essential for solving many (possibly all) problems in physics.

One of the best representations of boundary conditions in pop culture is in one of my favorite episodes of *Trek, Star Trek: The Next Generation*'s "Remember Me." In that episode, the ship's doctor, Dr. Beverly Crusher (played by the ever-brilliant Gates McFadden), faces conditions that put her skills and self-awareness as a scientist to the test. She appears to still be on the USS *Enterprise,* but crew members and guests keep disappearing—including her mentor and her son, Wesley. No one else seems to be noticing the disappearances. Dr. Crusher, with no evidence besides the disappearances, must deduce whether there is a real-world explanation for what's happening, because the alternative is that it's all in her head. Eventually, she looks out at the cosmos and notices there are no stars. She then asks the computer to tell her the size of the universe. The computer reports that it is 705 meters across—just under half a mile. Dr. Crusher is forced to conclude "If there's nothing wrong with me, maybe there's something wrong with the universe!" Thanks to an experiment gone awry, she is stuck in a pocket universe—a temporary universe where the boundaries are changing: They are shrinking.[*] Without an understanding of the bounds of her space-time, Dr. Crusher would have no hope of creating a scientific model for her situation.

"Remember Me" helps us understand that we need to know boundary information in detail. This is what Hawking and Ellis meant in the quote from a few pages back, where they say "there is the problem of the boundary conditions for these equations, and the global nature of their solutions." The information we start with is a mathematical formula, something with two sides and an equal sign in the middle. That formula includes information we know and also placeholders for what we don't know. Importantly, even after we figure out the missing information—the solution—we need to understand what the solution is telling us about the physical nature of whatever part of the cosmos we are studying. In other words, if we want to analyze the fundamental nature of space-time, we need to study the edge of space-time.

In the preface of their book, Hawking and Ellis lay it all out in terms of the physical problems that interest them:

> The subject of this book is the structure of space-time on length-scales from 10^{13} cm, the radius of an elementary particle, up to 10^{28} cm, the radius of the universe . . . This theory leads to two remarkable predictions about the universe: first, that the final fate of massive stars is to collapse behind an event horizon to form a "black hole" which will contain a singularity; and secondly, that there is a singularity in our past which constitutes, in some sense, a beginning to the universe.[6]

Just a few pages later they explain, "One can think of a singularity as a place where our present laws of physics break down. Alternatively, one can think of it as representing part of the edge of space-time . . ."[7] A boundary is the edge that determines what information or phenomena may be relevant to a problem. If the problem is to "understand space-time," then that boundary is the edge of space-time.[†]

The terrifying and exciting truth is that our cosmic point of origin is currently hidden from us beyond the edge of what our equations can tell us.

And that means we're just beginning. Alice thought she had seen it all when she went down the rabbit hole. But then she crossed a new boundary by going through the looking glass. In our own way, we are about to find that the metaphors that made space and time make sense to us can only take us so far on this journey, while a metaphor that we never expected to transform our relationship with reality will do exactly that. Learning about fields changed the way I saw the world, literally. It may do the same for you too.

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[*] I find it quite shocking that this brilliant film was a commercial failure, although it set the stage for the surrealist success of the 1939 film *The Wizard of Oz*. Who doesn't love Cary Grant in full costume as the Mock Turtle??

Go to note reference *

* “Phenomenology” is a tricky word to get a feeling for, but really what I mean here is the stories we tell about phenomena, things that are happening. See also: Ahmed, *Queer Phenomenology*, 1.

Go to note reference *

* He would eventually find that the answer is no—everything accelerates the same because the acceleration due to gravity depends only on the mass of the object exerting the force!

Go to note reference *

* It’s worth taking a moment to consider how velocity and speed are not quite the same concepts. Speed does not contain information about direction, while velocity does. If we change direction but keep going the same speed, as happens when a satellite orbits the Earth, this change represents an acceleration. Speed stays the same but direction changes. In other words, acceleration does not require a change in speed—a change in acceleration is sufficient.

Go to note reference *

* There’s no such thing as a pocket universe, but it’s a good science-fiction device!

Go to note reference *

† 10^{28} means a 1 with twenty-eight 0s after it—a much bigger number than a trillion, which is 10^{12}, or a million, which is 10^{6}.

Go to note reference †

CHAPTER SIX

BABY'S FIRST FIELD THEORY

In which we learn that light is a gateway theory

There is a great modern proverb: Shit happens. We take for granted that this is the case, that events are constantly occurring, change is always happening, and sadly, not necessarily for the better. Yet from a scientific perspective, we shouldn't take for granted the fact that anything happens. It all could have been otherwise, but somehow it isn't. Somehow space-time is out there, expanding, and particles and atoms are all over the place, moving.

We change in time, and these changes are directly related to motion. The idea that there is a relationship between matter and motion might seem to be the most natural one in the world, yet when considered in the abstract, it's also very deep. And old: As discussed in chapter 2, the Mohists, in 446–221 BCE, were already grappling with *why* matter moves. This is easy for us now, right? Gravity is one obvious reason that matter moves. But knowing this doesn't signify an understanding of how gravity actually induces that motion. The way we experience gravity suggests to us that it is an unseen phenomenon that acts instantaneously across space. It is as if there is an invisible tether holding us to the Earth's surface, holding the moon in the Earth's orbit, and holding the Earth and all of the other planets in orbit around the sun.

The fact of gravity is one of our daily indicators that "nothing happening" isn't really an option in our universe. Gravity also points us to the idea that the causes of motion have to be delivered throughout space-time by some kind of mechanism. In the case of gravity, that mechanism is space-time itself: Its curves foist motion onto matter, which is restricted to move according to the shape of space-time. Sometimes we describe the effect as a "gravitational field." Fields are our attempt to explain why things happen and how matter ends up in motion, governed by rules that tether a force to matter that is sometimes very far away from its source. Ultimately fields explain why the universe could never have been simply an empty abstraction with nothing in it. And in a perhaps surprising twist, light is the best gateway to understand why that is.

Electric Boogie

If you've ever been to a Black American wedding, there's a decent chance that at some point you did a line dance called the Electric Slide. This dance is set to the Marcia Griffiths song "Electric Boogie," which opens with the lines "*You can't see it / It's electric!*" That's the gist of a field: You can't always see it, but you usually can feel its effects. The electric field also happens to be part of what I like to call "Baby's First Field Theory," electromagnetism. This is an idea a lot of people have heard about (or danced to), but understand even less than gravity. Yet it plays a huge role in our everyday lives, pretty much every second of the day. It is also an intellectually stimulating phenomenon to understand—not simply because the ability to have command over electricity and magnetism has radically changed humanity's technological landscape but also because electromagnetism is the first physical theory that *needed* to be understood as something called a field theory.

Our childhoods are full of early experiences with electromagnetism, including stuff that might not have seemed like it was related to electricity or magnetism. As a kid, I had a beloved wooden block set, an incredibly generous gift from my Auntie Roz and Uncle George ז״ל, which I played with endlessly until it was gifted (against my wishes!) to a younger family member. With those blocks, I learned that it was possible to build structures that resisted gravity. My experiences taught me that because wood was hard, the other wooden blocks didn't fall through whatever was below them, including the hardwood floor of my childhood bedroom.

One of the things I loved to do with the blocks was construct courses that I put wooden train tracks on top of. I had little wooden trains with wheels that I pushed and pulled around, made up of multiple cars attached by magnets. Magnets, I knew, stuck to our fridge and also stuck to each other when I connected them. But there was a right and a wrong way to do this—sometimes the magnets repulsed one another and sometimes they stuck together. My train set included a bridge with a smooth incline that went up, peaked, and then went down. Over the course of many playtimes, I learned that I had to pull the train up the incline, but from the top it would roll down by itself before eventually coming to a stop. These were my first conscious experiences with friction, which is actually a collection of effects mostly related to how rough or smooth a surface is. If we were to zoom in on the rough parts to see what causes the friction that slows the train down, we'd see that the wheels of the train and the wood are not perfectly smooth. The little bumps and valleys at the molecular level resist each other, causing the train to slow.

While all this sounds intuitive, we should push against the explanation a little bit: *Why* would there be resistance at the molecular level? Why don't the bumps just pass through each other? The answer is that the atoms that make up the train wheels and the atoms that form the wood have electrons in them that repulse each other. This is also why the train never fell through my bedroom floor. My train set worked the way it did because of electric and magnetic effects, in addition to gravity. The work of physics requires pushing beyond noticing that things are happening—toward understanding what makes those phenomena not only possible but also, in many cases, necessary. Gravity is why the train goes down the incline. The way it slows down is required by a different force: the Coulomb force of electricity.

Superficially, the Coulomb force appears to be a lot like gravity. The electric force gets weaker when you move away from its origin point in the exact same way gravity does. The electric force also has a source—particles with a property called "charge" that is somewhat analogous to mass. You've heard of some of these particles before, electrons. But while mass characterizes how much stuff comprises a material thing, charge is simply a property that a thing either has or does not have. Also, while mass is always positive—you can't have an object made up of non-stuff—charge can be either negative or positive. As Ramamurti Shankar says in his beautiful textbook *Fundamentals of Physics II,* "Mass can never be hidden, whereas charge can be hidden."[1] We can always cancel out a positive charge with a negative charge, but it's not possible to cancel out mass because there is no such thing as anti-mass. (This is different from saying there's no antimatter, but that's for a later chapter!)

What is emerging here is that, like Transformers, matter has more to it than meets the eye. Particles have properties that we notice when we harness them, for example through electricity, but otherwise are not something we can "take a look" at. Physics is the thing that helps us look under the hood of a particle and start to make sense of it. Even so, it's easier to casually mention electric charge, as I just did, than to explain its origins and fundamental meaning. Charge is, abstractly, a property that a particle may have which causes it to experience the Coulomb force. This is similar to the way mass works with gravity. As I described earlier in the book, we can define gravitational mass as the property matter has that causes gravity to act on it.

But I realize that this comparison doesn't necessarily help you understand charge. In the case of gravity, we have an innate intuition for it because we have all experienced the fundamental asymmetry between things going up and down relative to the surface of the Earth. We all know that "what goes up must come down," and that means that down is special. But even with gravity, there are surprises—the mass of an object doesn't make it fall toward the Earth faster, but it does make it harder to launch.

We don't have that same intuition for electric effects, but we do have some direct experience with them. Consider your experiences with static. If you rub a balloon against your hair, your hair (especially if it's on the thinner and straighter side) will start to stick to the balloon, even though there is no visible adhesive. The rubbing causes some electrons to move from your hair to the balloon. The hair then is more positively charged, while the balloon is more negatively charged, and these opposites—positive charge and negative charge—attract. As a result, your hair will be inclined to stick to the balloon.

This sounds more like a party trick than something that will build your intuition for the idea of charge. But what is intuition, anyway? In her work *Knowing Otherwise: Race, Gender, and Implicit Understanding,* Alexis Shotwell describes the complexity of information that we sometimes know but don't always have a conscious description for, pointing out that many of our relationships with and conceptions of the physical world are like this. We know about at least some elements like gravity because we've thrown things up and seen them go down many times. We don't have to think about it. A close friend of mine who used to play baseball got up close and personal with how this works when he positioned himself in the outfield to catch a fly ball. Though he had positioned himself correctly, the ball hit him in the face when he failed to position his mitt correctly under the ball. The baseball breaking his nose was a lesson on gravity that he will probably never forget. But as I've already described, even our intuition for what gravity is has its limits. In the end, intuition is at least partially a matter of experience.

There is no magic trick that produces an expert on physics who has some agility with its calculations, just the daily labor of investigating how things work and developing a new sense of the world based on the new information. Thinking about the effects of electrical interactions is one way you can begin to develop an intuition for them. No one is born a physicist: Each of us must decide to make ourselves into one.

Magnets, How Do They Work?

There's an Insane Clown Posse song—"Miracles"—that's famous for the line "*Fucking magnets, how do they work?*" The next line says they don't want to talk to a scientist about it, which is too bad because we do in fact know how they work. Magnetism is a near-mirror companion to electricity. This might not feel immediately obvious because we seem to have very different experiences with these forces than we do with electricity. Until I went to college and took my first electromagnetism class, what I roughly understood about magnets was that they are made of certain types of metals, and when put closely together they either clung to each other or seemed to insistently reject each other. This attraction and repulsion is a manifestation of the Lorentz force, the magnetic equivalent of Coulomb's law.

Magnetism can be visualized: In Figure 6.1, you can see a bar magnet surrounded by iron filings. Because the iron filings are permanently magnetic, their response to being in the presence of a magnet is to align themselves with the force lines of magnetism. That's why you see the structure in the image that you do—the iron lines are making visible the magnetic force tentacles emanating from the bar magnet at the center. Something that's worth noticing is the way the lines seem to travel in a loop —there's no clear beginning or ending to the magnetic force line.

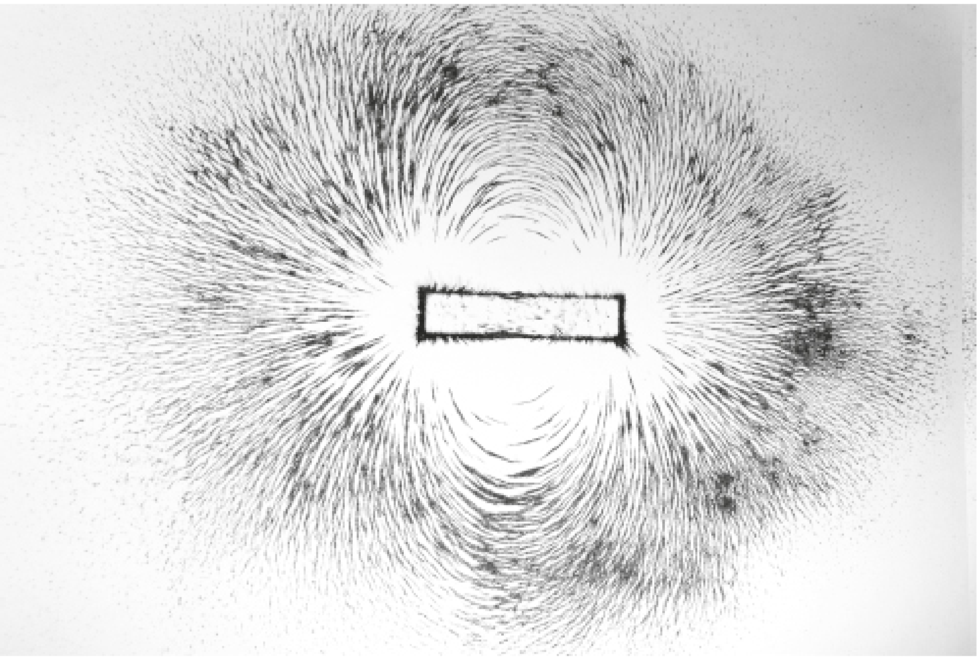

Figure 6.1. Here you can see a magnet in the center with magnetic filings aligning themselves with the shape of the magnetic force lines.

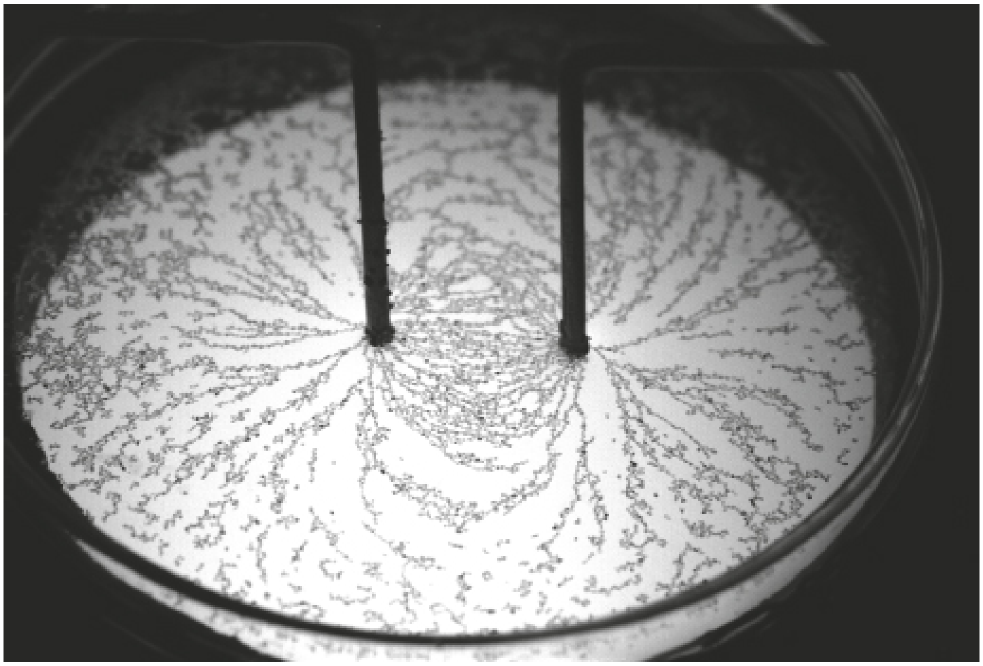

Figure 6.2. Here you can see a visualization of the electric field between two point charges, with semolina grains floating on castor oil. The semolina grains are following the electric field lines because when they are in an electric field, they become electrically charged.

Electrical field lines can also be visualized (see Figure 6.2). In that case, there is a clear starting point for the lines. This is what makes magnetism look different from electricity. While there is such a thing as an electric charge, from which electric force lines can originate, there is no magnetic equivalent. There is no magnetic charge. This is why there are loops of magnetic lines in the image, without a beginning or termination point. That doesn't mean electric and magnetic effects are completely unrelated; in fact, magnetic forces can be linked to the existence of electric charges.

There is a deep and inextricable connection between electricity and magnetism, suggested by the link between the electron (an electric charge) and the production of magnetic forces. One way to create a magnetic force is by moving an electric charge—creating an electric current, or flow of electric charge. When an electron moves, this creates a current. The movement of the electron and creation of this current causes the force created by the electron to change in time. This changing Coulomb force leads to the creation of a magnetic force. Going in the other direction, when a magnetic force is present for whatever reason, and it is changing in time, this creates an electric Coulomb force. Where there is electricity, magnetism follows close on its heels, and vice versa.

Electricity and magnetism are the kind of *weird* that physicists love because they invite us to explore. If thinking about them has left you scratching your head with questions, good. You should have a few. Some you might ask include: How are these forces acting at all? Is the force only at the exact location of its source, or does it extend beyond? And how does understanding these questions shape the way we see the cosmos?

This is yet another situation where the physical world foists upon us what can feel like an abstraction away from our sensory experience. Consider gravity in the Newtonian picture—not the relativistic one. In that scenario, masses experience action-at-a-distance attractions to each other, and this attraction is a force called gravity. I was told this so often as a child that I didn't stop much to think about how weird the concept of action at a distance is. Literally, whenever I stop to think about it for a second I immediately think, *But why would that be intuitive at all? Sounds like magic.* And it does sound like magic, that somehow massive objects are reaching out their tentacles across space and pulling on each other.

Of course, by now you know that gravity is just a name we give to the curvature of space-time. It is objects moving along the curves caused by the presence of mass on space-time's surface that give the appearance of a long-range attractive gravitational force. Knowing this, you might consider whether there's any analogue to the property of charge. And here is another place to remember that it's important to be able to recognize a metaphor and —as Robert Frost bid us—know its limits.

When we consider the relationship of the idea of mass to space- time, we are attempting to understand how masses move in space over a course of time. There is something very tangible about this, the science of motion. Mass and space-time are linked through the principle of inertia—that is, mass is a material object's resistance to motion. And the principle of equivalence is the notion that the inertial mass is also the same mass that captures an object's susceptibility to gravity.

By contrast, charge is a material object's susceptibility to the Coulomb force. There is no apparent external physical stage—like space- time—that charge can be defined relative to. There is no principle of inertia for charge. In other words, charge is a fundamentally different beast from mass and understanding how it manifests in the world requires yet another adjustment in perspective: the notion of a field.

Fields of Dreams

Fields invoke visions of specific outdoor environments. Some of my earliest memories are of trips to Dodger Stadium in Los Angeles's Chavez Ravine with my grandpa Norman, who grew up a Brooklyn Dodgers fan. So when I think about fields, one thing that comes to mind is my passionate love for baseball. But associations can vary.[*] My mother grew up in Barbados next to sugarcane fields like the ones our ancestors were forced to work just two centuries ago. Sugarcane fields are beautiful and also sometimes hard for me to look at because they remind me of the hardships of our ancestors' Middle Passage and journey through enslavement, and of how colonialism starved my mother's family when she was a child. It took me a few visits to Barbados before I stopped thinking about this history when looking at sugarcane and simply noticed the way the wind would move among the blades of the tall sugar grass on a breezy day. Wind takes time to arrive, and thus not all the blades are hit at the same time. Each interaction with the moving air particles is shaped by the angle of the blade and the direction of the wind, causing the blades to bend in a particular way. I was watching a wave move through a field.

In physics, a field is simply a physical quantity that has a value at every place in space and time, like the wind moving through sugarcane. It is a process that takes a location in space-time as input and outputs the strength of something at that location. The quintessential example of a field is the temperature in a room. Heat rises, so the temperature in a room is going to be warmer near the ceiling than near the floor. At every point in the room, a distinct temperature can be measured, and of course this measurement can also vary in time.

In fact, the word "field" in the context of a physics theory first appeared in the research notes of Michael Faraday during his experiments with bismuth (an atomic element that is the main ingredient in Pepto Bismol). Faraday was trying to figure out how to describe the effect of magnetism across empty space (and eventually established Faraday's law, which says a fluctuating magnetic effect will cause fluctuating electric effects). His notes from November 10, 1845, refer to a "magnetic curve or line of force." He then makes a further attempt to describe the effects he is seeing: "Wrought with bodies between the great poles, i.e. in the magnetic field, as to their motions under the influence of magnetic force."[2] What Faraday was describing is the way bismuth seemed to be attracted to force lines, spread out in what he called a "magnetic field."

Faraday's invocation of "field" in the context of magnetism was a powerful new abstraction that linked the old concept of a field of land to the more general sense of an area where a force is at work—like the Lorentz force, which describes the force that magnetic fields impart on a charged particle. One way of thinking about the electric field is that at every point in space, there is a value for the electric force that a charge would be subject to if it was placed at that point. But this is a bit unsatisfying because it makes the electric field sound like it is just a series of labels for points in space.

In reality, what is happening is that the charged particle—an electron, its antimatter equivalent the positron, proton, or some other particles we will learn about later—is emitting an electric field that is *physically* at all of these points. Eventually, when we get far enough from the source that the electric field is very weak, we can treat it as if it is functionally nonexistent and has the value of zero. This "falloff" happens as the inverse of distance times distance—which is to say that the farther we go, the weaker the field quickly gets. But this isn't just a set of labels. This is the presence of a real physical effect at points within the nonzero field distance range. The electric field is real, and the magnetic field is too.

I have a pet theory about why Faraday arrived at the word "field" to describe this apparent presence of magnetic qualities at each point in empty space. Faraday is often remembered as being unusual for a "man of science" in his era and place (early-to-mid-1800s England) because he did not come from an upper-class background. His father was a blacksmith who had grown up in farm country. According to the *Oxford English Dictionary* (*OED*), the word "field" is of Germanic origin and cognate with the Middle Dutch word "velt."[3] "Velt" meant "field of battle, open space in a town, area of space in a book, square on a chessboard, surface of a shield on which a charge is displayed." This has evolved into the modern Dutch word "veld," which the *OED* defines as an "area in which something operates (e.g., a magnetic field)." I see here a possible conceptual linking between Faraday's roots in a peasant family that lived off the land and the way he abstractly conceived of forces working at a distance in space.

Today, the name Faraday is probably most familiar in the form of Faraday cages, which are metal containers whose boundaries conduct electricity and prevent external electric fields from getting into the interior of the cage. This works because the field causes the charges in the metal to produce their own field that cancels out the external one. If you want to attend a protest with your phone but don't want your location to be tracked, one way to deal with this is to put your phone inside a Faraday cage. (This isn't legal advice, though.)

Let There Be Electromagnetic Waves!

In the Newtonian action-at-a-distance picture, a force acts instantaneously. There is no time delay. But this can't really make sense in a world where we know there is a speed limit—nothing can go faster than light. So we should ask what happens when we change the location of a charged particle. This means that the source for the electric field has moved. Is the change instantaneous? The answer is no. There is a delay as the information about the new source location and associated strength of the field changes. It takes time for the information to propagate, to travel. What's the speed that this change happens at? It turns out that this is the speed of light, though it would take some time for James Clerk Maxwell to show how this worked.

Two decades after Faraday first applied the word "field" to the physical phenomena at work, Maxwell synthesized everything known about electricity and magnetism into a single unified theory (sometimes called Maxwell's equations). In his 1865 paper "A Dynamical Theory of the Electromagnetic Field," he wrote, "The electric field is the portion of space in the neighbourhood of electrified bodies, considered with reference to electric phenomena."[4] Notice that these words directly describe the electric field as a "portion of space." He identified the electric field as a fundamental property of the space around a charge. This isn't quite how we think about it today, but as I was working on this chapter, I couldn't quite convince myself that we shouldn't. Perhaps this is the true meaning of saying that the field exists everywhere.

Maxwell was following in Faraday's footsteps, grappling with the notion that every point in space around a charged object (particle, current, and so on) seemed to be endowed with the capacity to act on another charge-sensitive object placed at that point. Here we already have the hint that electricity and magnetism go hand-in-hand. It turns out that the connection is quite deep. Electric fields and magnetic fields are not actually separate phenomena but two sides of one phenomenon—the electromagnetic field.

To understand how this is possible, let's return to the Coulomb force. The simplest electric field is one where the source charge is not moving. Then the electric field is static, unchanging. But of course we can have situations where the charged particle is moving or where there are many particles moving. These movements lead to an electric field that changes with time, at a finite speed. When we write down Maxwell's equations, they all point to the solution of a system of differential equations (remember those from the last chapter?) where the electric field and the magnetic field look like waves moving through space and time.

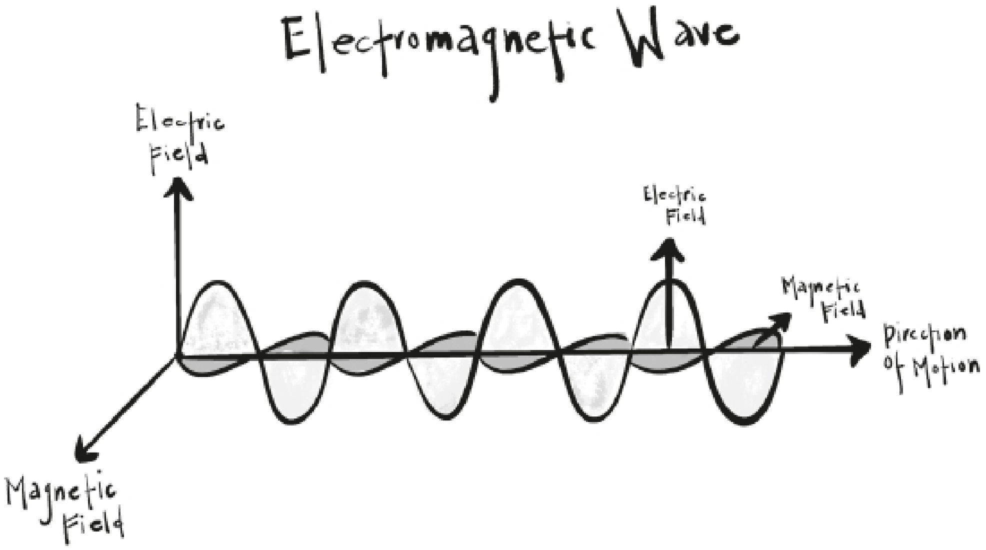

Figure 6.3. Here you can see the magnetic field and electric field propagating to the right together as a combined electromagnetic field. They are always at 90 degrees from each other, like two walls intersecting.

In Figure 6.3, you can see a graphical representation of an electromagnetic wave as it travels through space. What's missing from this image is that the wave also exists in time. So, using the picture and a bit of imagination, you can see that a wave is a thing that goes up and down in space—and it can also move forward in time while it goes up and down. A wave is characterized by two major properties: the amplitude (how high and low it goes, so how high the top of the curve is), and the wavelength (the length of the crests between the points where the lines intersect with the direction of propagation). We can substitute the frequency of the crests for wavelength, if we prefer. For any wave, it is a bit of simple math to calculate the frequency if you know the wavelength, or the wavelength if you know the frequency. The thing that connects them is the speed of the wave. Maxwell showed that in the case of the electromagnetic field it was a constant number: The wavelength times the frequency is always the same number, the speed of light.

Based on this realization, Maxwell hypothesized that electromagnetic waves *were* light. In hindsight, this isn't a guarantee. There is another kind of wave—gravitational waves, which are ripples in space-time caused by massive objects (like two black holes interacting) and also travel at the speed of light. Maxwell didn't know about gravitational waves—that would have to wait for the advent of general relativity, the theory that predicts their existence. Maxwell naturally drew the connection between light and electromagnetism.

In the course of drafting this chapter, I had to figure out how to explain that electromagnetism and light are the same phenomenon. This is taught to first-year physics students as a foregone conclusion, a postulate that we should simply accept. In reality, there was a fifteenyear gap between Maxwell's 1865 hypothesis and Heinrich Hertz showing the connection in his experimental work. Hertz was doing some experiments with conductors —materials that allow electron charge to flow—when he noticed that generating electricity in one of the conductors caused a spark to appear in the other one. This led him to build an experiment that produced what we now call radio waves. In a series of subsequent experiments, Hertz showed that these radio waves were the same as Maxwell's predicted electromagnetic waves.

Thus, Maxwell's formulation of "electromagnetism" and Hertz's experimental follow-up had an astonishing set of results: evidence that there is a single electromagnetic phenomenon, that a wave can travel through it when it is disturbed, that this wave is light, and that light travels at a constant speed through space (which is to say that the speed never changes in time). The other transformative realization was that electromagnetic waves could continue to exist even when a source is not present. As Shankar says in his book, "They can survive on their own, untethered from charges and currents."[5] He goes on to explain that this is because once the electromagnetic wave is there, it is carrying energy that can't just disappear. For these reasons, electromagnetism (also known as electrodynamics) became a moment of reckoning that would send shock waves into the future, a transformation that we are still coming to terms with today.

Let me pause to say I know that it can be hard to really feel the significance of that intellectual moment. And the dates involved can be distracting. Anytime anyone mentions 1865 to me, the history of physics isn't what I think of first—nor is it probably what most people think of. When I see that date, I think about how in 1865, many Black communities were still throwing off the chains of enslavement and trying to survive the bondage of settler colonialism and displacement. I think also about how in 1905, when Einstein published his first relativity paper, Reconstruction in the United States was over, replaced by a Jim Crow regime where the violent white nationalist group the Ku Klux Klan was a powerful and quite mainstream organization. While Maxwell and Einstein were free to let their minds wander, families like mine across the Americas and beyond were denied the same kind of opportunity to wander through wonder.

But it's important to remember that even so, the first African American PhD in the United States, Dr. Edward Bouchet, earned his doctorate in physics from Yale in 1876, just a few years before Hertz's experiments. The subject of Bouchet's dissertation was refractive indices in gas—how light travels in gas. Hertz (who was ethnically Ashkenazi Jewish) went on to a distinguished career in pre-Nazi German physics, but American racism meant that Bouchet never had the opportunity to continue his career as a researcher. Upon completion of his PhD, he was not welcome to join the faculty of any major research institution in the United States. That didn't stop him from using his skills, though it did limit what he could accomplish with them. As an instructor at the Institute for Colored Youth—now known as the historically Black institution Cheyney University—he taught physics and astronomy. It is likely that among the subjects he taught were nascent ideas about electromagnetism, including his own experimental contributions to a scientific understanding of light's behavior in different environments. When given the option, at least some of us will always choose to follow our curiosity about the inner workings of our universe.[*]

A Whole New Space-Time

Electromagnetism can be hard to understand, because the wildly abstract theory that the observational evidence points us to doesn't really draw at all from our daily intuition. It's also an example of how challenging our intuition and learning to think with that abstraction can be radical and game-changing. At the same time that Edward Bouchet was teaching some of the earliest alumni of a historic Black university, Einstein was thousands of miles away, wondering about how to explain electromagnetic transmission through space. The 1905 paper in which Einstein introduced special relativity has a title that might be surprising to the lay reader; "The Electrodynamics of Moving Bodies" does not sound like it's about how space and time mix. There is a tendency to introduce general audiences to relativity from the perspective of moving bodies and light, without discussing any details that underlie the science of light. Such a discussion doesn't seem necessary to make the point—just mention that the speed of light is constant, and you're good to go.

But the paper in which Einstein made the case for special relativity opens with a discussion of "electrodynamics" (another word for electromagnetism), and after introducing the principles that undergird special relativity and how they affect motion, the rest of the paper focuses on this topic. The reason for opening with electrodynamics is that one of his motivations for exploring the implications of a constant speed of light in a vacuum was a theoretical result that preceded experimental verification that the speed is indeed unchanging. Einstein wrote in the second paragraph of his world-changing paper: "The phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest."[6] Indeed, if you stop to think about it, the fact that the speed of light is constant in a vacuum means that light can never stop in a vacuum—not only is there no rest for the wicked, there is none for light either, it turns out. But this created a problem that Einstein's paper opens with: Electromagnetism was apparently inconsistent with Newton's sensibilities about absolute rest in absolute space that changes with respect to absolute time, because photons never rest.

And so one way to think about the game-changing history of relativity is to understand that special relativity naturally emerged as a consequence of trying to understand what happens when electric and magnetic fields are produced by moving charged particles and the attempt to synthesize this knowledge with established Newtonian precepts. Einstein's 1905 paper reflects this duality: First he applied the ideas to the motion of neutral objects, those that are familiar from Newtonian analyses, and then he worked out the implications for moving objects that are not electrically neutral and are instead electrically charged.

Special relativity offered an important reframing for electromagnetism. All the discussion earlier in this chapter about when an electric field is produced and when a magnetic field is produced was on some level *frame dependent*. Which is to say, it matters what frame someone is in and whether it is an inertial frame (return to chapter 3 if you need a reminder of what that means). An observer who is accelerating relative to a charged particle will perceive the presence of electric fields and magnetic fields differently from someone who is stationary relative to it. This is another way of thinking about the material physicality of the electromagnetic field. There is a single electromagnetic phenomenon, and whether we perceive its parts depends on our relative state of motion. Thus, one person might measure an electric field in a charged system, while someone moving relative to them might measure a magnetic field instead. Neither is wrong. They're both seeing the same electromagnetic field; it just looks different depending on their state of motion.

We could also consider the reverse scenario, where the observer is stationary and the particle is accelerating. A good example of this is an electron moving in a circle, perhaps in orbit around the center of an atom. The electron is accelerating, because whenever something moves in a circle, the direction of its motion is constantly changing; thus, even at a constant speed, something in a circular orbit is always accelerating. An observer watching a charged particle in such a circular orbit will witness it radiating an electromagnetic field, a mix of electric and magnetic effects that then go off into space and exist independently of their source as packages of energy sent off to make their own way in the universe.

The first lesson here is that electromagnetism demands a relativistic perspective—where the observer's frame of reference determines what they see. The second lesson is that special relativity is the thing that updated mechanics as a framework so that it could also contain electricity and magnetism. This understanding laid the groundwork for a radical shift in how we conceive of the *way* material phenomena occur in and interact with space-time—how shit happens. Electric and magnetic fields are valuable teachers because they show us that something can be happening where there is otherwise nothing physically there. The electric field can have value at a point where there is no object. This is not a property that is specific to gravity and, unlike gravity, it is not due to the fundamental shape of space-time. Instead it is an immaterial phenomenon that happens within space-time, with real material consequences.

Light is a powerful intellectual guide for us. It was a fundamental fact about light that pointed Einstein, Minkowski, and others to understanding space and time as space-time. Trying to explain how matter radiates light also forced scientists to take their first steps toward a quantum perspective.

To make complete sense of how light particles are both consumed and emitted by atoms ultimately required a merger of relativity and quantum mechanics, leading researchers to create a wildly rich mathematical framework called quantum field theory. When the dust settled, we were left with the idea that particles are actually material manifestations of fields that exist at every point in space-time. Electromagnetism was the first hint that such a thing was possible and that the fields were not an abstract idea, but rather real material objects. And quantum field theory pushes our use of metaphor to new heights by teaching us the most curious lesson: We are all abstract contraptions made from nothing. You'll see what I mean by this, when we go through the looking glass in Part III. But to appreciate the wonder of being an abstract phenomenon that came from nothing, you need to understand a bit about the queer phenomenology of quantum mechanics.

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* Even associations with Dodger Stadium. A lot of mostly Mexican American families were forced out of Chavez Ravine so that the Dodgers could build there.

Go to note reference *

* To learn more about Dr. Edward Bouchet, have a look at *Edward Bouchet: The First African-American Doctorate,* edited by Black physicist and community historian Dr. Ronald E. Mickens.

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II.

QUEER PHENOMENOLOGY

A NOTE ON “GREAT” MEN OF SCIENCE

There’s no good time or place to say this, but I have chosen here because fuck if I was gonna open the book with it. I already wrote extensively in *The Disordered Cosmos* about the “people problems” of physics, and I won’t write the same book twice. But it is important to make a note about the scientists whose ideas we spend the most time with.

There is a bizarre cultural tendency to treat physicists in particular as fascinating enigmas whose brains exist beyond the realm of everyday human politics. This isn’t true. The universe—including the human corners of it—is enigmatic, queer, surprising, and endlessly fascinating. But we physicists are just people, no more and no less.[*]

People who saw the 2023 Christopher Nolan film *Oppenheimer* may have walked away with the impression that the early 1940s were the glory days of genius white men who very unfortunately had to deal with complex moral questions and often made bad choices. In the chapters to come, some of the men portrayed in *Oppenheimer* appear, as do individuals from the same era who aren’t represented in the film. Some of them were real assholes. I mean assisting Nazis. I mean pursuing romance with underage teenage girls. I mean not doing much to facilitate the participation of women in physics, ignoring the internment of Japanese Americans in concentration camps during World War II, doing little to push the boundaries of Jim Crow, and allowing women to be relegated to second-class social status, subservient to them. Even a bright thinker can be among the worst of us. You’ve already met a famous example: Isaac Newton, who invested in enslavement and, as master of the Royal Mint, was an unforgiving cop.

While you read, if you're going to think about names, don't just pay attention to the names on equations or the names I strip from equations (like the quantum-wave equation, which typically shares the same namesake as the quantum cat). Think about all the names that might have been part of the story if their housework counted as a contribution to science, or if they had not been denied the opportunity to participate in the technical work. Think of the Japanese people—more than 300,000 of them—who were murdered with the American atomic weapons developed by some of our most widely honored scientific heroes. Think of the Native peoples whose land and communities were poisoned by nuclear weapons testing in the American Southwest and the Pacific Ocean.

The history of physics is fascinating, showing how people arrived at certain lines of thought, so I don't want to minimize the signifi-cance of historical events. I also believe that citation is an important historical and political practice, especially when it comes to people who are not well-known and whose identities might place them at the margins of established power structures. People like Chien-Shiung Wu, who (for better or for worse) made important contributions to the Manhattan Project, but, like most of the women scientists, didn't make an appearance in Nolan's film.

History is populated by people, and people can be a lot of things, including creative and terrible at the same time. So you'll find me occasionally citing and quoting people at length because their ideas were interesting. Don't conflate the ideas and the people. I believe that someone else would have worked out every aspect of quantum mechanics if the people who did it hadn't. Maybe differently, maybe at a different time, maybe with different styles of notation. But the universe is always there for us to understand—all of us. No one person or group has been fundamentally granted unique purchase on it. It is up to us to decide whether our social relations will continue to be organized around thinking otherwise.

Also, while I have you, I want to remind you that it's okay to reread something that feels confusing for you the first time, and also: There is no test at the end of the book. Enjoy the ride, however it manifests for you. That's your only assignment.

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* I'd love to see a more sustained attention to figures like Marie Curie's son-in-law, Frédéric Joliot-Curie, a French nuclear physicist who opposed nuclear weapons from the start, even as he saw peaceful potential in the work. He was punished dearly for his genuine commitment to French Communism. For more on him, see: Sweet, "France's Oppenheimer."

Go to note reference *

CHAPTER SEVEN

THE BOOK OF NONSENSE

In which photons are
curiouser and curiouser

Sense . . .

As a child I loved Edward Lear's *The Book of Nonsense,* a collection of limericks—five-line poems with a specific rhyme scheme of AABBA. The rhymes were often preposterous and therefore contained amusing setups, situations that we'd never expect anyone to find themselves in. But because of the well-defined limerick structure, while the poems were social nonsense, they followed a very careful rhyming and narrative formula. For that reason, they always made sense to me, to the point where I developed the ability to come up with limericks on the spot, a party trick I sometimes used to impress fellow physicists in grad school. Lear's limericks taught me to play with words, to worry about fitting the pieces together according to the rules of the form, rather than according to human social patterns.

That was my entry point to the different forms that rational sense can take. It turns out that developing an early appreciation for whimsical nonsense has served me well as a scientist. This kind of nonsense oriented me—in the sense that Ahmed discusses in *Queer Phenomenology*—toward asking and thinking through questions about phenomena that make me feel off kilter. Take for example "Old Man in a Boat":

There was an Old Man in a boat,
Who said, "I'm afloat! I'm afloat!"
When they said, "No, you ain't,"

He was ready to faint,
That unhappy Old Man in a boat.[1]

Is the Old Man in Edward Lear's limerick afloat? Is the boat real?

At first, the answer seems contingent on a disagreement between two observers; a matter to be settled, perhaps, by the listener. We don't learn the actual answer in this poem, though personally I'm Team Old Man. We don't really need to know the answer about this hypothetical situation. Instead, what we need to appreciate is that there are some questions whose answers seem obvious but actually aren't, and also that we live in a world of fundamental uncertainty regarding what is material.

The Edge of Classicality

So far in this book I've discussed physical theories that work in what we physicists call the *classical* sense: Given the correct differential equation and the right initial conditions/boundary conditions, I can make a definitive prediction about what will happen next. This is true in Newtonian mechanics, special relativity, and general relativity. And it also comports with common sense about reality.

If I hold a glass jar of peanut butter and drop it onto my kitchen floor, I know it will go down, hit the ground, and probably break. I know for certain that jelly won't spill out of it when it hits the ground—because before I dropped it, it was filled with peanut butter. I am also confident that it won't hover next to me (unless my kitchen is in free fall in an elevator or in a low-gravity environment in outer space). I *know* all of these things because on the scale of everyday life, the physical world we know tends to behave like it always does.

Our lives are organized around the notion that we can be certain about outcomes if we exercise sufficient control over the initial conditions. We hang our entire sense of what constitutes rationality on the idea that there is only one logic at work in physical theories and that they are deterministic. For many of us this is intuitive; for the rest, we are taught that it is what our intuition should be.

In general, physicists work to identify the state of the system, or the collection of properties that characterize the system. In chapter 3, "Space-Time Is the Place," I focused on the example of my car on the freeway. There we might characterize the state of the car by its location, speed, and direction at any given instant. That's enough information to tell you the future location if the speed doesn't change. It also tells you all the information you're likely to want to know about the system at any given moment of time.

The physics meaning of "state" is yet another example of the way science takes words we think we know and endows them with new meaning. The state of a physical system is limited and rigorously defined. It's not nebulous like "state of mind," which has no set parameters that are used to characterize it. It's also not a sociopolitical arrangement, like a geographic state with borders that are obviously socially constructed and sometimes highly contested, often because of colonialism and other nonsense. By contrast, the physicist's definition of "state" appears to promise a circumscribed concept of status, one that is easy to determine and follow in sequence.

With a car in motion, we expect that we can identify the location, speed, and direction with fairly detailed accuracy, given the right instruments. There will always be some error, of course, but luckily the mathematical area of statistics helps us characterize that error. But appearances can be deceiving. This sense that we can take measurements like this that are definite, plus or minus a small possibility of error, is what we might call a classical, as opposed to quantum, sense. In this scenario, we believe that there are definite, singular, and even predictable answers to our questions, given all the necessary information. We do not necessarily imagine the possibility that we can have all the relevant information and still not know for sure what will happen.

Personally, I believe electromagnetic fields already violate what we might call "classical sensibilities" in science. The field concept seems so abstract that it can be hard to convince yourself that it's real. In that sense, it's not surprising that electromagnetism was a vector for a different kind of change in physics too. It's a kind of tip that there's more to the universe than what Isaac Newton's laws encourage us to imagine. This becomes evident when we study an idealized physical system called a blackbody (sometimes written as "black body").

In her poem "quantum distributions for Sarah Baartman," physicist and poet Lena Blackmon summarizes the idea at hand, brilliantly linking social understandings of black bodies with the physicist's conception:

> here is what *is* true:
> a black body radiator be a star that Rayleigh Jeans Law fails to approximate[2]

Blackmon is making careful, metaphoric use of the dual meaning of "black body." One meaning we often see in the media: Black people's bodies which are too often, due to racist violence, dead Black bodies. The other is the physicist's concept of a blackbody. They are linked in a way. We African-descended peoples are racialized as "Black" in part because of the melanin that we have in our skin.[*] This melanin is a molecule that absorbs light, something the physicists' blackbody does perfectly.

Blackmon's metaphor helps us understand this meaning of black-body: a physical body that absorbs all light that is incident on it, regardless of the frequency of the light or the angle at which it hits the blackbody. Blackbodies are not only ideal light absorbers; they also are light emitters. As highlighted in Blackmon's line above, one example of a real physical object that approximates a blackbody is a star. In other words, the blackbody is a physical model for objects like stars that absorb light and also emit across the electromagnetic spectrum—the full range of frequencies (or wavelengths) of light. A natural question follows: Given our understanding of electromagnetism, can we make predictions about how light will be emitted by a blackbody like a star? Specifically, how much energy will be in that light at different frequencies?

If we use classical electricity and magnetism theory, like that described in the last chapter, it's fairly straightforward to calculate how much energy there will be in different frequencies. Classically, the amount of energy associated with a frequency increases with frequency. There's only one slight problem: There are an infinite number of possible frequencies. So, the classical model predicts that as we increase the light frequency, the amount of energy emitted will eventually become infinite. The equation that can be derived to show this is called the Rayleigh–Jeans law—the one that, as

Blackmon points out, fails to approximate a star. In other words, we can do the calculation, but the answer is infinity, and this is a nonsensical answer because there is no infinite source of energy.

The only way out of this problem is through a new idea. In the original classical electromagnetic framework, the value of possible energies is continuous—all numbers are possible. But if we instead consider the possibility that they are quantized—specifically, if we assume that the possible energy values are discrete and that light is, instead of a continuous wave flowing like the ocean, a collection of discrete packets of energy—everything changes. Think about it like the track numbering on the latest Yves Tumor (or BTS, etc.) album. We would never expect them to release an album with track numbers 1, 1.01, 1.02, etc. Instead, the tracks are numbered in discrete whole numbers: 1, 2, 3, and so on. In this scenario, there is a direct correlation between energy and frequency. This creates a situation where at high frequencies (short wavelengths), a lot of energy is required to produce light packets. This requirement for high energy makes the phenomenon less common at high frequencies and an infinite energy impossible. This makes the infinities disappear, and instead the relation between wavelength and energy output looks like a nice hill (see Figure 7.1).

Moving from continuous energy levels to discrete—quantized—energies may sound like a small change, but it is not. To propose that light-wave energy is somehow quantized is to suggest that light is made of what we now call quanta—individual, discrete packets of energy. This is outside the realm of our classical sensibilities about how energy can change within a system and how light interacts with matter. It suggests that our classical picture is limited, and in fact implies that light is a form of matter. And matter, at least as we know it, comes in particles. But didn't we just establish that light is a wave, the electromagnetic wave to be precise? A particle, you'll remember, is an object of finite extent and individual manifestation. By contrast, a wave is a continuous phenomenon—ripples spreading out and traveling outward from their origin. Light, it appears, is playing both sides.

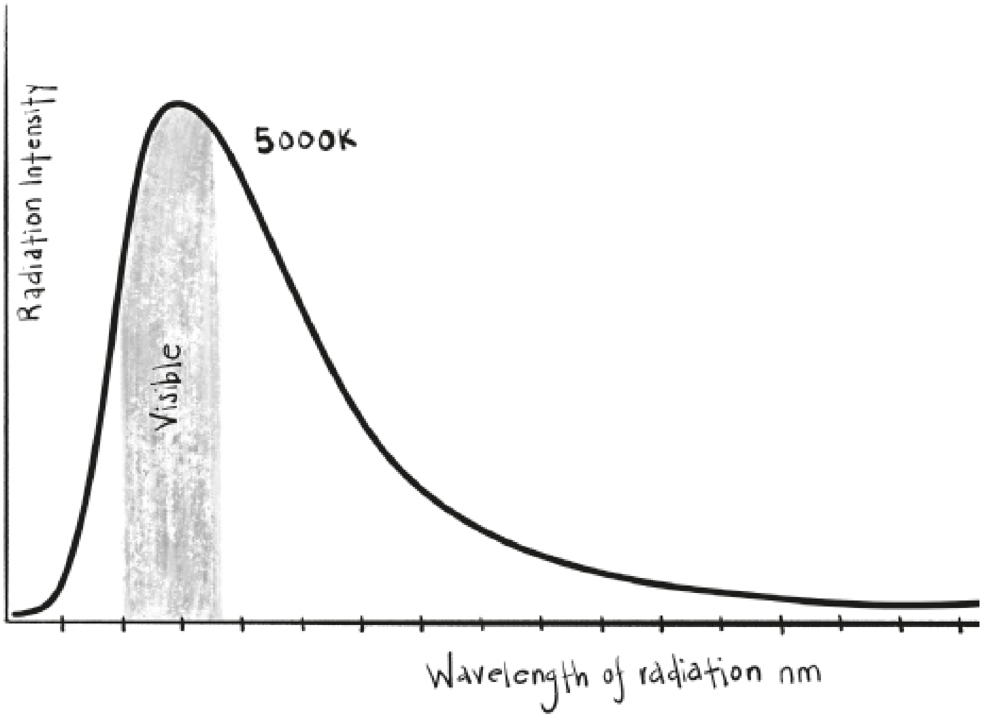

Figure 7.1. This is a blackbody spectrum—light power in different wavelengths—for an object that is 5,000 Kelvin, about 8,500° F. On the vertical axis going up and down is the intensity of the light, and on the horizontal axis is the wavelength of the light. We could make a similar figure using frequency instead of wavelength since these two parameters capture the same information.

The idea that something could be a wave and a particle at the same time sounds like a category error—like I'm mixing up an ox and a horse. But it's not whimsical nonsense, a fact that I hope some experiments will convince you of. The first is the double-slit experiment. Here's how we do it: First, we prepare a laser, which is a type of light source that produces a very focused light beam in a very specific color. The laser is shot at a plate with parallel slits. The pattern that forms behind the slits on the wall is the kind of pattern we'd expect to see with a wave, as you can see in Figure 7.2.

This seems pretty normal, what we'd expect: Light is behaving like a wave. But we can set up another experiment where we shoot light at a material. The light is a carrier of energy, so we expect that the waves will transfer energy to the electrons in the material. In some cases, the electrons will become so energetic that they jiggle out of place and separate from the material. What we find in the experiment is that the electrons will only depart if certain energy thresholds are met. There is a minimum energy packet that the electron needs to receive before it appears to notice the energy at all. And even if we turn up the intensity of the light, the departing electrons don't get more energetic, though the number of energized electrons increases. What matters is the frequency of the light.

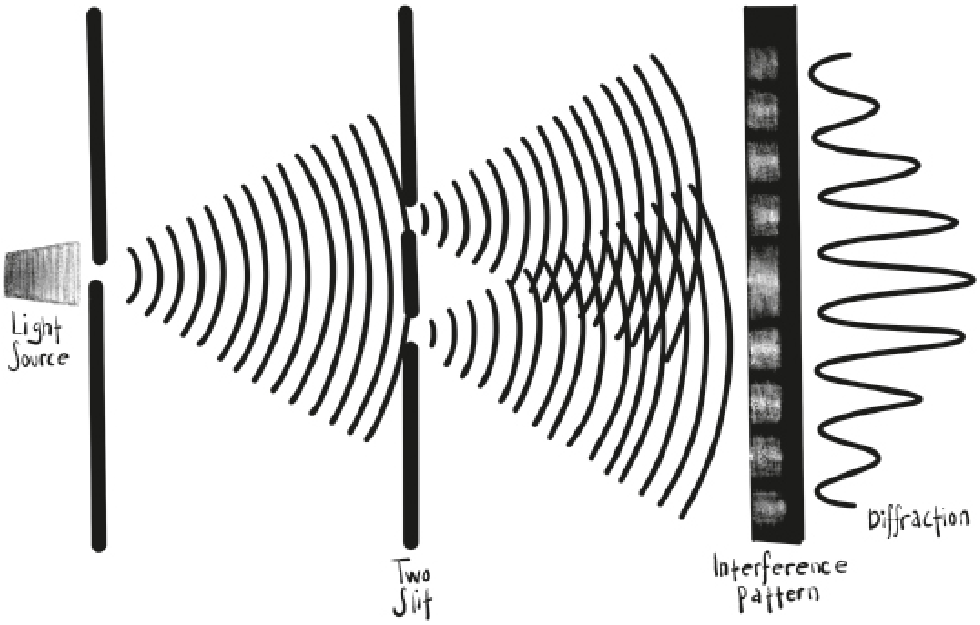

Figure 7.2. In this experiment, the light is sent through two slits and creates an interference pattern on the wall. The bright and dark spots correspond to places where the light combines to have a stronger visual signal and the places where the light interference has a dampened strength, respectively. The pattern on the right edge, which is a representation of the combined strength, is called a diffraction pattern.

This phenomenon, known as the photoelectric effect, means that the electron has to have a minimum amount of energy to make its escape from the material, and that energy correlates with the frequency of the light. The results of this experiment made Albert Einstein conclude that the energy associated with this leap has to arrive in distinct individual packages—discrete parts that correlate with light. These little packets of energy are photons, particles of light.[*]

Kindly pause and consider what's happening here. What we see with these two experiments is that light behaves like a wave and a particle. I'm not telling you that light is sometimes a wave and sometimes a particle. I'm saying that it is always both, just as some nonbinary people understand themselves as being both man and woman, simultaneously.[*] In the case of light, this dual existence is known as wave-particle duality, and light's particle-like nature is enshrined in a new particle called the photon. Wave-particle duality means that light really is a form of matter, rather than a phenomenon that is distinct from it.

Alongside wave-particle duality we also have the implication that energy levels may be quantized in some physical systems—including, notably, atoms. There is also another physical revelation at work: the quantization not just of the material thing (light into photons), but also the idea that energy distributions are discrete and quantized. If this happens to light, and light is a particle, then we *should* wonder whether it happens with other particles too. And if it happens with particles, then surely it should manifest in objects made of particles, like atoms, which themselves are the basis for molecules.

In 1918, Elmer Imes, the second African American to earn a doctorate in physics, published his PhD work on hydrogen chloride, hydrogen bromide, and hydrogen fluoride molecules, showing that the quantization was observable in their energy levels too. These results provided important affirmation that the quantum picture was relevant, not just for light and other fundamental particles like electrons but also for larger structures like molecules. Imes's work resolved an ongoing controversy among the new quantum physicists, whose experimental work until that point had been inconclusive about the quantum nature of molecules.[†]

Imes's research on molecules was an example of experimental work that confirmed that light/photons isn't the only wave/particle duality out there. In fact, all particles have this duality. In Figure 7.3, you can see evidence of this from doing the double-slit experiment again, this time with electrons. What you're looking at is real data, not an illustration. In Box (b), electrons going through a double slit hit a detector, and the hits look just like little holes, as if a golf ball went through a screen. Looking at the subsequent boxes, as more electrons go through, a pattern emerges. It looks a lot like the one with the light, right? By the time you get to (e), the wave-like pattern is obvious, and so is the visual overlap with Figure 7.2. The electron, which we can literally see lands on the detector like a particle, also behaves like a wave in how it lands.

The lesson? The theory of quantum mechanics has to be a theory of waves.

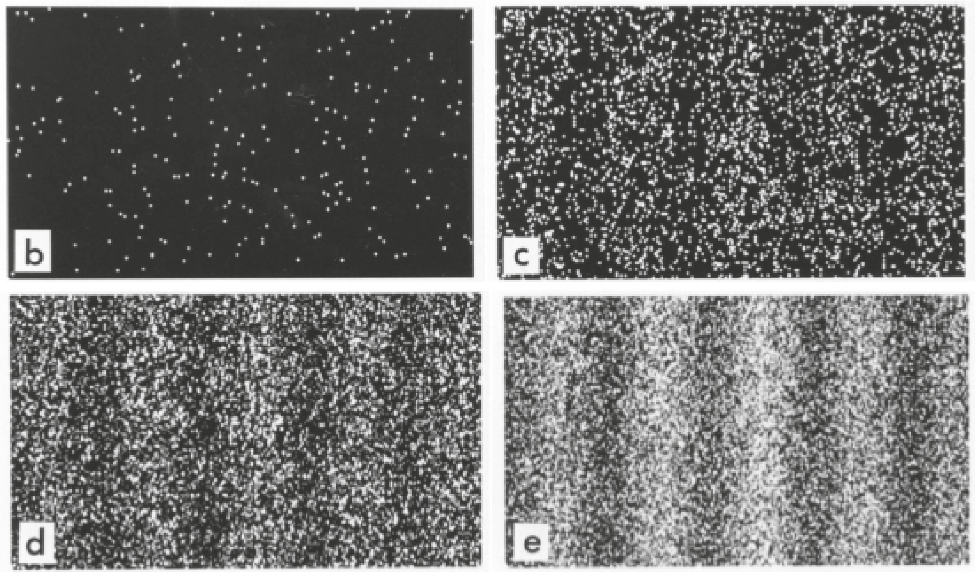

Figure 7.3. Not a drawing: This is real experimental data from a team led by Dr. Akira Tonomura showing that electrons shot at two slits eventually show a pattern that looks just like the one we see from light waves. At the same time, we can see that each particle is hitting the detector one at a time. One problem this experiment raises is, which slit did the particle go through? The interference pattern suggests it went through both, the way a wave would.

. . . and Sensibility

Before I go any further, I'm warning you now: Just as Alice took a little bit of time to get to the bottom of the rabbit hole, so will you. To go deeper into our present understanding of the cosmos, you have to get familiar with the beauty and confusion of quantum mechanics. We have our taught notions about how we get information about the world, and then we have a set of experimental results that present challenges to this worldview. Quantum mechanics is the story of the smallest things we've ever seen forcing us to reconsider the fundamental nature of the entire universe.

And just as reaching the bottom of the rabbit hole was only the beginning for Alice, so too is it the case that knowing a few things about quantum mechanics mostly just means that you are better able to characterize how unable we are to make total sense of the world. And there is endless possibility in the apparent nonsense we find ourselves confronted with. We are told over and over that it is not intuitive. Maybe it's not—I can't speak to what may seem intuitive to you. But if quantum mechanics doesn't make sense to you, that's an excellent problem to have and a fine place to begin. It means there is a place to grow in your understanding of what actually is normal for our world, and to come face-to-face with the boundary that demarcates what is known and what is unknown. This is the place where we are invited to reevaluate, to get creative with what we thought we knew, to learn how to tell a more complete story of our universe.

On the other hand, maybe it will make sense to you. That's beautiful in a different way. Either way, I hope this discussion can open up new language, new metaphors for your own life. For example, British-Iraqi drag queen Amrou Al-Kadhi once replied to Channel 4 News (UK) that nonbinary identity made perfect sense, since after all a particle can be a particle and a wave at the same time. Wave- particle duality became an entry point for Al-Kadhi to make the case that gender deviants and dropouts like me may find that the most fundamental principles of the universe are a suitable metaphor for our most intimate experiences. This invocation of quantum mechanics as a metaphor for queer existence is an example of what becomes possible when we spend time learning about the cosmos.

Having seen that we are learning new metaphors, you should ask the question: What is the theory that underlies these properties of light? We need a quantum theory that will give us the state of light, a quantum theory of light-particle waves.

We actually had something of a problem the whole time when it comes to matter. Newton's laws assume the existence of matter but don't tell us anything about its composition. Nor does general relativity, or special relativity for that matter—they just give us rules that we think should govern matter, without telling us what exactly matter is made of. I was forced to think about this by Paul A. M. Dirac, who made key contributions to the theory of quantum mechanics. He is one of my favorite thinkers on the question of what physics is supposed to do and why classical physics isn't enough. In his 1958 book *The Principles of Quantum Mechanics,* Dirac points out:

> We have here a very striking and general example of the breakdown of classical mechanics—not merely an inaccuracy in its laws of motion, but an inadequacy of its concepts to supply us with a description of atomic events. The necessity to depart from classical

> ideas when one wishes to account for the ultimate structure of matter may be seen, not only from experimentally established facts, but also from general philosophical grounds.[3]

Dirac goes on to point out that if we assume that each piece of matter is made of smaller and smaller divisible pieces, then we can continuously go to smaller and smaller distances and masses—what physicists refer to as length scales and mass scales—to seek out matter's foundational building blocks, with no end in sight. But ultimately, the idea of quantum energy packets—energy coming in individual chunks—suggests that there are minimum scales beyond which things cannot be sliced down further—there is an edge beyond which we cannot go. A minimum mass scale means there is a minimum energy scale. "It is therefore necessary to modify classical ideas in such a way as to give an absolute meaning to size," Dirac concludes. Quantum theory invites us to go searching for the smallest matter, knowing that it must exist.

It also presents opportunities. Classical electromagnetism suggests that matter shouldn't be stable: As you'll soon see, quantum theory solves the problem. The relative stability of matter, of course, is something that we tend to take as a given. People typically remain assembled without our compositional atoms spontaneously decaying. We may worry about our eventual deaths, as our organs malfunction at an increasing frequency with age. But the atoms underneath them all? They are persistent—and, on the timescale of a human life, generally unchanging.

It is the purpose of physics to explain how everything in the universe works, so it is insufficient to be satisfied with the fact that atoms are stable for long enough to form hydrogen and make heavier elements like carbon and oxygen and form planets, at least one of which has (perhaps catastrophically for our planet) evolved humans. We know that this happens; our very existence is evidence of atomic stability. But the physicist's job—at least in the case of a theorist—is to be unsatisfied with knowing only an empirical fact while having absolutely no explanation for it.

Given that the atom is comprised of a nucleus and electron(s), we can use the physics we know to investigate this system's dynamics. The natural approach is to combine Newtonian mechanics with electromagnetism, something that you now know special relativity helps us with. So far, so good, except now there's a new problem: These two theories in combination suggest that the atom should be extremely *unstable*.

In the scenario where we think of the nucleus as the sun and the electron like a planet in its orbit, electromagnetism teaches us that a charged particle like the electron will emit energy when it's changing speed or direction—in other words, when it's accelerating. To get some intuition about this, think about the *Fast and the Furious* film franchise—people are often driving at high speed in a straight line. Now imagine that a driver makes a sharp turn. Because objects that are in motion tend to stay on that trajectory, everything in the car will try to go straight.[*] This is why it can feel like we're being pulled against the turn when we're in a car making a turn—your body is trying to go the way it was already going, but the driver has used the car to create a force that pulls your body in a new direction. This change in direction is a type of acceleration.

An electron that is orbiting an atomic nucleus would be constantly turning, in the sense that a circular orbit is unending turning. In other words, the electron would constantly be accelerating. Anytime an electron accelerates, it radiates energy, like it's leaking gas. A loss in energy should mean that it can't hold itself in a stable orbit. So the energy loss due to the electron's orbit should cause the orbit to decay, meaning that the electron should crash into the nucleus, destabilizing the atom. And yet hydrogen and many more massive atoms are stable, which is a good thing for us because, again, if atoms weren't stable, structures wouldn't be able to form and there'd be no stars, no planets, and definitely no us.

In other words, classical electromagnetism on its own would preclude us from existing. This is a pretty epic problem—for a theoretical physicist, anyway—and it's not one special relativity helps us solve at all. Laws of physics, especially relatively well-tested ones like Newtonian mechanics and electromagnetism, should describe reality. But here they offer a picture in which structures in the universe would cease to exist. They are an utter failure at explaining why matter holds together in any complex fashion at all. This is not the kind of crisis that should lead to panic; this is the kind of catastrophe that a theoretical physicist loves, because it means there's work to do and some fraction of the universe still waiting to be fully understood.

As it turns out, the solution to the problem of how to make matter stable is worldview-altering. Niels Bohr tackled this problem in a creative way, taking seriously the lessons about quantization learned from Max Planck's resolution of the blackbody problem as well as Einstein's explanation of the photoelectric effect. Through a combination of imagination and intuition rooted in his knowledge of basic physics, Bohr developed a model in which the electron could only be in discrete orbits at set distances from the center of the atom—the electron somehow knew its place and simply stayed in it. This would prevent electron orbits from decaying, thereby protecting the integrity of the atomic structure. It was an imperfect proposal because it did not explain why. But, baby steps—sometimes we draw the picture and worry about why it makes sense later.[*] Bohr's proposal was known as spatial quantization, and it had big implications for other properties, such as how magnetic forces would affect the motion of an atom.

The idea behind spatial quantization is that instead of being able to orbit the atomic nucleus at any distance, there are discrete levels that an electron can exist in. You can think of these limitations on electron energy levels like a building that limits capacity based on number of people. In this scenario, only one electron is allowed per floor. If each orbit is akin to a building floor, one way to think about this is that if we were to number the available orbits, they could only be described by whole numbers—numbers with no decimal after them. So it could be distance of 1, but not distance of 1.001. More generally, an electron can be at location n, where n is any rounded number with no decimals, or location $n+1$, but it cannot be at location $n+0.001$. This was the idea behind Bohr's model, though again he had no explanation for why the atom might have this structure. Not long after he proposed it, Arnold Sommerfeld proposed a modification: one where the amount of rotation is quantized into discrete values. It was a creative leap that lined up with what physicists were already discovering about the quantum nature of particles. Atoms are stable because of quantization, as you shall soon see.

There was a theorist named Otto Stern who was completely horrified by Bohr's idea. When he tried to prove Bohr wrong, he helped open the door to an aspect of the universe that forced a shift in our sensibilities about what is real and what is material. As in Lear's limerick, there is apparent nonsense, but also an underlying structural logic. In the quantum world, particles have physical properties that don't seem to emerge *from* our physical space—at least, not in the sense we are used to—but whose effects nonetheless manifest here. It is Stern's fault that we know particles spin without spinning. It is to this story that we now turn.

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* Readers who are curious about this should check out the chapter "The Physics of Melanin" in my first book, *The Disordered Cosmos*.

Go to note reference *

* Einstein won the Nobel Prize for this—and not for relativity. It's easy to feel intimidated by how many significant contributions he made. And Einstein was a smart man. But also he made contributions at a time when it was easier for someone to know everything there was to know about physics.

Go to note reference *

* There are also nonbinary people who do feel they are more one than the other at different times. Nonbinary experiences are diverse!

Go to note reference *

† For more on Elmer Imes, who married Harlem Renaissance great Nella Larsen in 1919, see research by fellow Black physicist and community historian Dr. Ronald E. Mickens, "The Life and Work of Elmer Samuel Imes."

Go to note reference †

* This is actually Newton's first law/Mozi's law. The fact that we need it here gives you a sense of how these seemingly small statements have far-reaching implications and applications.

Go to note reference *

* My late postdoctoral advisor Ann Nelson ז״ל taught me this lesson while I was working with her. I worried about how to justify an interesting particle- physics theory. She told me that sometimes there's a moose on the wall with a purple scarf, and you'll have to worry about *why* later. For now, we just explore the moose in the scarf. This is how a lot of particle theorists do their work, especially phenomenologists, those who are concerned with possible or observed phenomena.

Go to note reference *

CHAPTER EIGHT

THE QUANTUM TURN

In which we are compelled to accept that quantum physics has a point

> "You'll see me there," said the Cat, and vanished.
>
> Alice was not much surprised at this, she was getting so well used to queer things happening.
>
> —Lewis Carroll, *Alice's Adventures in Wonderland*[1]

It is rather unfortunate that *Alice's Adventures in Wonderland* missed the advent of quantum mechanics by just decades. The Mad Hatter's tea party might have taken on a rather different and even more dramatic flavor if Carroll had known that nonsense wasn't just a joke and that reality is most accurately described by a theory that could reasonably be called a silly, irrational riddle.

There is a moment in *Alice* when Alice is speaking to the Caterpillar, who is lounging on a mushroom with which Alice is now eye- level. Alice explains to the Caterpillar that she is quite unhappy to be so comparatively short. He says that to grow taller she only needs a bite of one side of the mushroom, and to be shorter she only needs a bite of the other side. This is of course totally ludicrous: The mushroom's top is roughly circular, and a circle has no sides. But this story could have been transformed had Carroll known about the concept of quantum superposition of states: the idea that an object can simultaneously occupy two entirely different states of being. Read through the lens of quantum mechanics, the Caterpillar's mushroom is no longer so nonsensical. Only the act of measurement—which in the case of Alice and the mushroom would mean her consumption of the different samples—leads to the object choosing to be in one state or another. Quantum-mechanically speaking, only when Alice bites into the piece of mushroom does it become either a piece that causes growth or a piece that causes shrinkage.

Commonly, after a certain age, a human's height is fairly stable. And people don't flicker out of existence suddenly—we've never seen a sudden disassembly of someone's atoms because the electron orbits decayed. But in Wonderland, Alice's state is quite unstable. She's not in reality—at least, not as she previously understood it. Meanwhile, consuming the mushroom may change her height, but it's not clear how until she eats some of it. And if we try to talk about her status, we now need to somehow consider the possibility of some height fluctuations. Similarly, at the heart of quantum mechanics is a need to change how we think about what constitutes the state of a system. The variables we need to account for may be different, and there's a lot more uncertainty.

Not everyone was on board with quantum mechanics in the beginning. The Stern–Gerlach experiment began as an effort by Otto Stern to disprove an idea that is now fundamental to quantum mechanics. This experiment is, to me, the definitive proof that our universe is fundamentally quantum-mechanical in nature, and it also helps explain why atoms are stable. The mathematics implied by the Stern– Gerlach experiment force us to accept that while the rules of quantum mechanics *sound* surrealist or nonsensical, quantum phenomena are very real. If you can accept the results of the experiment, you're on your way to developing a feel for the quantum nature of the universe, which means experiencing a complete reconfiguration of the way you look at matter. That's what happened to me, anyway.

An Idea Born of Dislike

There are different ways to begin this story. Here's one: It all started just over one hundred years ago, in 1922, when theoretical physicist Otto Stern and experimental physicist Walther Gerlach teamed up to prove Niels Bohr wrong about the atomic structure proposal I described at the end of the previous chapter. In the end, Stern and Gerlach accidentally and partially succeeded, and gave us an experiment that forces us to rethink the whole universe. Another version of the story might start with the fact that Stern was a Jew, and while Gerlach wasn't an enthusiastic Nazi, two decades after teaming up with Stern he held a leadership role in the Nazi nuclear program. Still another version of their story could begin with the fact that Stern was a theorist who proposed an experiment only Gerlach could pull off. One more equally true beginning: Niels Bohr and Arnold Sommerfeld had some very radical ideas about the atom; Stern hated the implications and set out to prove Bohr and Sommerfeld wrong; Stern ended up proving them right.

To prove Bohr–Sommerfeld quantization wrong, Stern proposed an experiment that was then conducted by Gerlach. The basic idea of the experiment was to shoot a beam of silver atoms through a magnetic field created by a magnet (on the periodic table, silver is represented by Ag due to its Latin name, argentum).[2] As you can see in Figure 8.1, the silver atoms are heated in a furnace before being beamed toward the magnet. The magnet has a north component and a south component—this part of the experiment is important because it means that the magnetic field varies from top to bottom. This variation creates a force on the silver atoms.

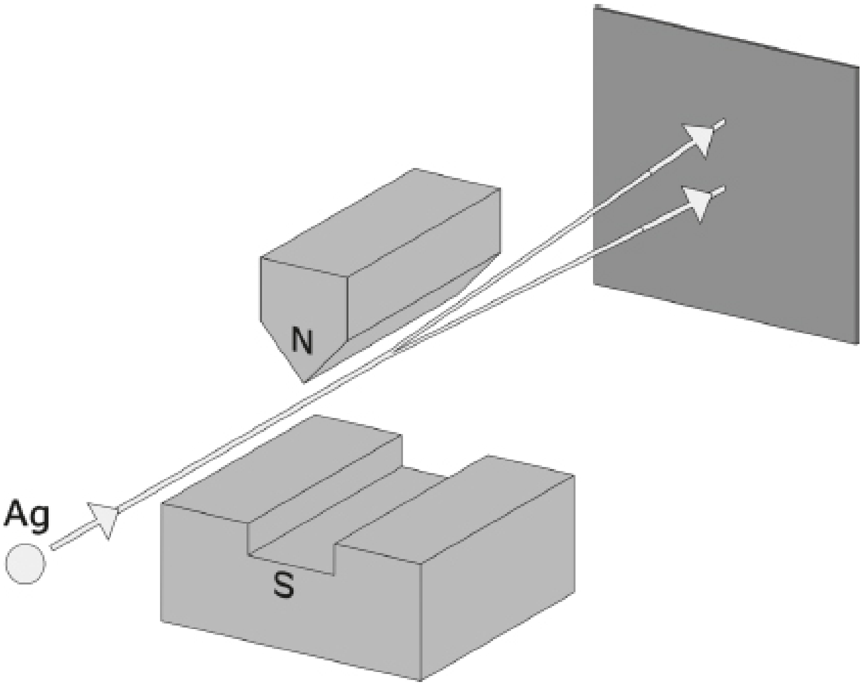


Figure 8.1. The experimental apparatus. On the left there is a source of heated silver. The silver atoms are shot out in a beam that goes through a pair of magnets with a north and south

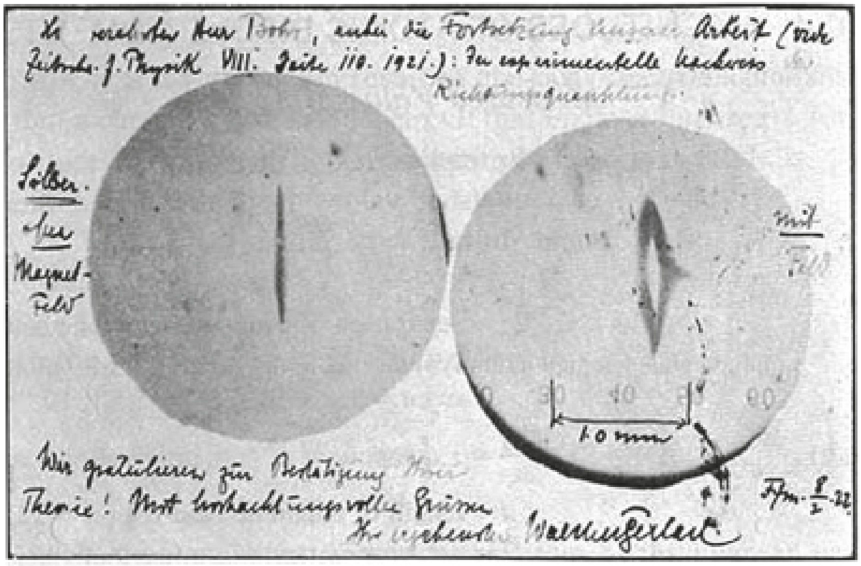
component. The difference in the shapes of the magnets causes a magnetic field that changes with location, which leads to a force on the silver atoms. The classical prediction is that this would cause the atoms to land in random locations roughly directly ahead of the detector, maybe with a bit of fuzzy distribution for random variations in field strength and initial speed of the atoms. This figure suggests to you what happens instead, which you'll see for certain in the next figure.

Here we have to pay close attention to what physical properties of the system are important. We have a magnetic field, and this matters because of the force it imparts. The force matters because it signals the presence of something else, momentum. Physically speaking, how much force an object is experiencing is given by how much its momentum is changing in time. When I think about momentum, I think about a big-rig truck and how it takes a longer time to stop than a smaller car. That's because it is more massive and has more momentum—its combination of mass and speed is more powerful than the small car's. For similar reasons, getting hit by a 10 mph baseball throw hurts a lot less than a 90 mph Sandy Koufax fastball. In my head, I associate "momentum" with amount of "mmmphh"—something has to push things around. So the presence of a magnetic field means that there's the potential for "mmmphh" to happen.

In the Stern–Gerlach experiment, the force created by the magnetic field is key because it is proportional to the *angular* momentum of the atom's outermost electron—a measure of how much rotational force is being applied to the electron over a given time. If there is angular momentum, then there will be a force. This force determines where the silver atoms will hit the target.

In the scenario where there is no quantization—where the Bohr–Sommerfeld model is wrong—one would expect that the atoms would hit the target in random fashion, leaving atoms hitting spots all around the target. This is because the angular momentum could take on any value, with no numerical limitations. But in the scenario where there is spatial quantization, things would look quite different, because there would be rules about which values angular momentum could have. For example, if there are only two angular momentum values, then there are only two possible force values and only two possible regions on the target where the silver will hit.

To Stern's chagrin, what they found was that all the atoms landed in one of two locations—one up and one down—and not in between. Classical physics offered no possible explanation for this result. It is a fundamentally quantum result. Stern and Gerlach sent Bohr a postcard (pictured in Figure 8.2) telling him that he was right: “The experimental proof of directional quantization. We congratulate you on the confirmation of your theory . . .”



Hochverehrter Herr Bohr, anbei die Fortsetzung unserer Arbeit (vergl. Zeitschr. f. Physik VIII. Seite 110. 1921.): Der experimentelle Nachweis der Richtungsquantelung.

Silber. Ohne Magnet-Feld

mit Feld

Wir gratulieren zur Bestätigung Ihrer Theorie! Mit hochachtungsvollen Grüssen
Ihr ergebener Walther Gerlach

Ffm. 8/2. 22.

Figure 8.2. The postcard they sent Bohr. On the left is the experimental outcome when the magnetic field is off—the particles randomly land along one line directly ahead of the detector. On the right is the outcome when the magnetic field is on—they are deflected to two lines, one up and one down. The lip shape comes from the fact that the magnetic field gets weaker farther away from its source, the magnets, which makes the lines bend together. A more constant magnetic field would produce two lines that never connect, one of spin-up particles and one of spin-down.

A Sequence of Peculiar Events

The results of the experiment were revolutionary, and also everyone involved initially misinterpreted them. Only later did scientists understand that silver didn’t have an outer electron with orbital angular momentum. So angular momentum had been detected, but not the kind that Stern and Gerlach thought. It wasn’t until around 1926 that people understood what they had actually shown: Electrons have a quantum internal rotation that we now call spin. This spin doesn’t manifest in the real world the same way a spinning figure skater does. Even so, it is real, with observational consequences, as Stern and Gerlach showed.

To really appreciate spin, it's useful to go back to the classical, Newtonian mechanistic picture of the world, and to our discussion of what we mean in classical physics when we talk about the "state of the system." Formally, the "state" of a system (such as a particle, or a baseball) is given by two pieces of information: its position and its momentum. In classical Newtonian mechanics, both position and momentum are quantities that are simultaneously measured. These can change with time. Think about what happened every time Brooklyn Dodgers star Jackie Robinson hit a home run: He changed the direction and speed of the baseball with his bat, imparting enough momentum to carry it past the outfield. There are equations that govern the trajectory that the ball could take, and if we know the speed of the ball at the time of impact, the angle of impact, and the force of the swing, we can correctly calculate whether any outfielder had a chance of catching it or whether it would defy gravity long enough to make it into the stands.

These equations, which physicists call equations of motion, are completely predictive solutions to the differential equation that is Newton's second law of motion, $F = m \times a$. They always give us a firm answer about what's happening. Once we have the initial pieces of information about the moment of impact—the initial conditions, we call them—we know the laws of physics that govern how the ball will behave. Repeat these conditions, and the ball will do exactly the same thing, 100 percent of the time. In the classical picture of physics, this should be true for atoms and particles too.

But the Stern–Gerlach experiment—despite not being correctly interpreted off the bat—eventually made it clear that we can no longer think of states of systems in these classical terms. The results of the experiment show that particles have a property that *mimics angular momentum*—which, remember, is momentum associated with rotations—*but does not manifest as actual motion.* The particle displays mathematical properties like a spinning ball, except there is no spinning! The experiment further implied that this intrinsic angular momentum—spin—is quantized, meaning that changes to it can only be via adding or subtracting multiples of one, like n and $n+1$. But n does not need to be a whole number—it can be a multiple of a half. An electron has an intrinsic spin of $n = ½$. In the case of particles that are spin-½, as we call such particles, they can have two different possible spin states:

½ (spin up) and −½ (spin down), which we will label using up (↑) and down (↓) arrows, respectively.

Spin, like angular momentum, has a sense of direction. And we can measure angular momentum in all three of the spatial directions: *x, y,* and *z* (see Figure 8.3 to orient yourself). Classically, we can always measure these properties simultaneously. So, if spin were a classical phenomenon, we would always be able to measure the spin (up or down) in each direction—getting values for spin-*x,* spin-*y,* and spin-*z*—at the same time. But spin is not classical at all, and it has no classical analogue. Spin is, in my opinion, the most quantum of all particle properties.

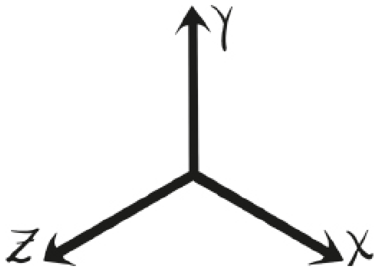


Figure 8.3. The three directions formalized as *x, y,* and *z.*

We can see this by looking at a series of Stern–Gerlach experiments, done sequentially. So, instead of just doing one experiment, we do two, or even three. Using these sequences, we can check to see what happens when we simultaneously measure spins in different directions—keeping in mind that the value is always one of two possibilities, up or down. In the following there will be a lot of arrows, and it's okay if you decide to draw your own diagrams! Make up equations—whatever you need to help you follow the discussion. For those who just want to coast, I'll flag for you when we've come to an important conclusion.

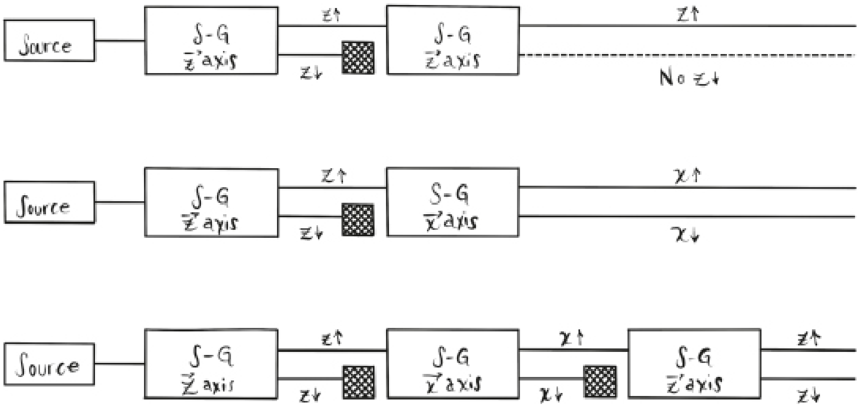


Figure 8.4. Three sequential Stern–Gerlach experiments, showing the potential outcomes described in the text.

We start with the top of the three diagrams in Figure 8.4. Here the first sequence has a magnetic field pointing in the *z* direction, which produces an outcome of two beams of particles with the properties spin-*z* up (*z*↑) and spin-*z* down (*z*↓), respectively. Then, we capture all the *z*↓ and only let the *z* ↑ particles move ahead to the next Stern– Gerlach experiment, in this case another *z*-direction magnetic field. The outcome is as we might expect: We only see *z*↑ particles. The lesson of sequence one appears to be that we get out what we put in.

Next, consider a second sequence in the middle of Figure 8.4. This one begins the same as the first one, except the second experiment in the sequence now has a magnetic field pointing in the *x* direction instead of the *z* direction. The particles leave this experiment in two beams of particles: spin-*x* up (*x*↑) and spin-*x* down (*x*↓), respectively. Importantly, because the last experiment in this sequence had a magnetic field only pointing along the *x* direction, we only get information about the aspect of spin that is correlated with that direction. Here's what we learn from sequence two: We can only get information about the last spin direction that was measured.

Now we get to the third experiment in Figure 8.4, at the bottom. It is identical to the second sequence except with a third experiment added onto the end: measuring spin in the *z* direction, again. After the second experiment in the sequence, we have two beams of particles that are in the *x* ↑ and *x*↓ states, particles that you might recall started out in the *z*↑ state. So, at this point we might be thinking, *Well, we know these particles have* z↑, *regardless of their spin value in the* x *direction.* Thus, we should expect that if we send only the $x\uparrow$ particles through another z-pointing magnetic field, the particles will know that they are $z\uparrow$—because that's how they started. Measurements in the x direction shouldn't affect them.

Put another way, we might reasonably assume that the second experiment should have no bearing on the third. We did nothing to the particles except look at them—to separate out the group of $x\uparrow$ particles. We assume that nothing about the x-direction magnetic field would have stripped the particles of their z-direction identities or made them forget what state they are in. After all, we didn't change anything about the particles except for how we looked at them. We should only get $z\uparrow$ particles.

What actually happens next never stops tickling my brain. Half of the atoms come out $z\downarrow$! Because we measured their z-direction values, half the particles lost their established $z\uparrow$ identities! Apparently, the act of observing them changes their properties. We can measure spin that "points" in one direction or the other, but not both of them simultaneously. Measuring in the x direction makes particles lose information about what their spin in the z direction was.

Honestly? Holy shit! Like Alice choosing a "side" to the mushroom, we are now in a situation where it seems that observing an experiment can change its outcome.

Seriously.

When I last taught this to first-year graduate students, they were quite upset, because it sounds like nonsense. *But it's what happens in the lab,* I insisted. *We have got to accept it!* We deal in observables. Truly, the rest of the universe does not care whether what we see feels counterintuitive to us.

And it gets worse. Let's consider one more step, shown in Figure 8.5: This one is similar to the last sequence, except we don't block the $x\downarrow$ spins after they exit the second apparatus. We let all of the atoms pass through, together, into another z-direction experiment. What is your best guess about what happens next?

Using your newly developing intuition about the particles, you might think they'd split evenly between $z\uparrow$ and $z\downarrow$. Yet this fourth one has a bizarre outcome: The particles all go into the $z\uparrow$ state. As shown in Figure 8.5, they seem to "remember" their z identities after all—but only if we don't measure their x identity. The lesson that you need to remember, even if the details don't all stick: We can look at the *x* properties or the *z* properties, but not both. The act of observing plays a definitive role in what is observed.

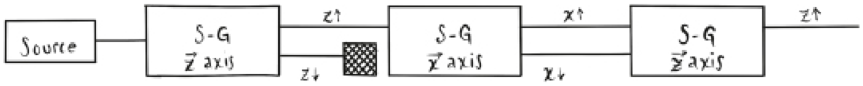


Figure 8.5. The fourth sequence is an even bigger surprise than the last one. Somehow the particles have maintained information about their *z* state.

How?

If you feel like this doesn't make sense, that's a correct feeling. Everything we know about objective, detached observation seems to be violated here. Why would the properties of the particles be sensitive to observation to the point of changing their status based on it? How can the information possibly disappear and then be reencoded on the particles?

There are a few perspectives on this. Let's start with the one that is among the least mainstream and also perhaps the most interesting when it comes to research: Maybe we don't have enough information about this system to make clear predictions about it. This is known as the hidden-variable viewpoint. The idea behind the hidden- variable concept is that there are some other pieces of information—variables—that are currently hidden from us, and that is why we don't have complete predictive power about what particle will go where, or which particles will turn out to be spin-up and which will be spin- down. It's not such a wild idea to believe that there may be hidden information or assumptions.[*]

Another way of thinking about this is that we have found ourselves in a situation in which the measurement *itself* disrupts the system. There is no separation between the observer and the observed, at least not in the ways we are used to thinking about, for example, measuring the speed of a car that is passing us on the highway. But this is not a relativistic effect! This is due to the existence of spin—apparent rotation with no visible spinning—as a purely quantum phenomenon. Measuring spin affects the outcome of the experiment because spin is a quantum property. And there is no way to be more clever, to make the system such that we can observe it without interfering with it. Taking this at face value, it turns out that we can't measure spin in the *x* direction and spin in the *z* (or *y*) direction simultaneously. This is our first contact with the idea of incompatible observables that are subject to an uncertainty principle.

The results of experiments three and four suggest to us that there are two utterly different outcomes that depend on what we measure. The particles may "recall" certain information about their spin, or they may not. Remember Alice's mushroom, which seemed to be in a state of making things grow bigger and making things grow smaller at the same time? This superposition of states—being in two states simultaneously—is what happens to the particle spin in one direction when we measure it in another. When we measure $x\uparrow$, the particle is in both $z\uparrow$ and $z\downarrow$ state—$x\uparrow$ is a superposition of $z\uparrow$ and $z\downarrow$. You can think of this as being kind of like simple arithmetic, $x\uparrow = z\uparrow + z\downarrow$. And, similarly, $z\uparrow$ is a superposition of $x\uparrow$ and $x\downarrow$, with $z\uparrow = x\uparrow + x\downarrow$. (These equations aren't literally correct, but they are schematically correct.) This is classically impossible, and yet Stern and Gerlach made it happen in a lab.

Everyone Here Is a Wave

There is much to adore about the Stern–Gerlach experiment. There's the historical story of upended expectations, plus the time a theoretical physicist proposed what turned out to be a critically important experiment. (Most of us are too incompetent at experiment to be so useful!) There's the way it pushes us to understand how physicists actually arrive at understanding a new-to-us idea: by being miserably wrong, by fighting our intuition, and by developing a new feel for things through intense intellectual labor.

Stern and Gerlach showed us that what was classically impossible is now quantum-mechanically plausible. Their experiment also points us to a physical phenomenon that has real-world physical consequences but also seems to not actually be happening in our world, at least not in the traditional sense. In the Stern–Gerlach experiment, the silver atoms behave as if they are spinning. But they aren't really spinning in the space we live in. That is so strange and wonderful! This should feel like a nudge to wonder: What counts as physical existence? In what sense is the spin of these particles "real"?

We know for sure that there are real experimental results showing a model of spin without spinning. We also know that this model has rules that govern it: It matters in what direction we measure spin, since that determines what information we think we know about the system and its history. And the system doesn't "remember" information about past spin along other axes, which suggests that, in the past, it possibly turned in any of these directions. But we don't know; there is still a limit to what we can know for certain. The fact of quantum contextuality, the idea that what we know about the present doesn't give us certain information about the past, is one of the forms of uncertainty that arises in quantum physics.

The other is Heisenberg's uncertainty principle. In its simplest rendering, the uncertainty principle tells us that we can't simultaneously measure the location and momentum of a particle with perfect accuracy. The more accurately we know the one, the less accurately we know the other. No matter how perfectly we do the experiment, there is a fundamental limit on the information available. In his book *The Logic of Scientific Discovery,* philosopher Karl Popper proposed a statistical interpretation of Heisenberg's uncertainty equation.[3] From his perspective, the uncertainty principle indicated that if you have a population of identical particles, there will always be some spread in measurements of their position and momentum, no matter how perfect our experiment is. The inability to measure spin in two directions simultaneously is another example of an uncertainty or indeterminacy relation, and it is mathematically derived in the exact same way as the original one.

The Heisenberg uncertainty principle can be applied to pairs of spin measurements as well as position/momentum pairs because of the distinct mathematical structures that seem to be essential for describing the observed physical phenomena. This presents a problem for defining the state of a system, since now we only can know position or momentum with any kind of certainty. We also now know that particles have a fundamental nature that is wave-like, which suggests they should be described by a wave; plus, properties like spin somehow need to be accounted for. The most obvious solution is to search for an equation of motion that will describe a wave—a differential equation we can solve, assuming we have the right boundary conditions. Happily, thanks to electromagnetism, among other things, we know quite a bit about wave equations, and a full system of wave mechanics can be built around this concept. But the *physical* interpretation of the equations is quite different from what Newtonian mechanics teaches us to expect.

In quantum physics, all the physical information about a particle is contained in something called a "wave function," the quantum version of an equation of motion. The state of a system is now given by this wave function, which is not a model of how the particle looks in space or how it is moving. The formula *describes* a wave, but it is not a wave that exists in the real world the way an ocean wave does. It is a formula that gives us probabilities about the particle's properties like location, momentum, spin—and no clear explanation of why we get one particular outcome or another when we take a measurement, just the likelihood that we will get any given one. A song I listened to *a lot* in graduate school—Cloud Cult's "Everybody Here Is a Cloud"—helps us think about this. The song says that we "*came up from the ground / from a million little pieces*." Yes and no. We are a composition of orders of magnitude more than trillions of particles; the "million" is too small. But it's true that we are kind of cloudy—we are somehow the manifestation of a series of wave probabilities, a batch of particle likelihoods working in tandem with one another. Now, you may ask, is this way of thinking just a useful abstraction, or is it "real"?

The answer is . . . complex. In quantum mechanics, the state of a physical system is no longer simply encompassed by the position and momentum, properties that can be characterized using numbers that have real-world analogues. The number five, for example, can correspond to five toes. We can count them out. Five is a real number. But in quantum mechanics, the state of a system is given by a wave function that does not "live" in a physical space the way that, say, position does. To describe a wave function *requires* us to use numbers that aren't even real. We have to move from a mathematics that uses numbers that can be connected to real physical objects to something more abstract.

Instead of living in our three-dimensional space alone, a wave function lives in something called Hilbert space, so named after German mathematician David Hilbert.[*] Hilbert space is a mathematical formulation of the concept of "space" that is more general than the one we are typically used to, and it deals in both the familiar real numbers and something called imaginary numbers.[*4] This sounds like we are in Learian *Book of Nonsense* territory, like we've stumbled on *Sesame Street*'s Count von Count's worst nightmare: numbers that won't count bats.

The Count shouldn't worry. This situation is why Stern–Gerlach is so great and one of my all-time favorite experiments. It teaches us two things. The first lesson is that information can apparently disappear and then reappear—and whether this happens apparently depends on the presence of an observer. That's weird. But the second lesson is perhaps even more surreal: To mathematically characterize the results of this experiment, to write down equations that match what we observe, we must use a type of number that has no physical counterpart. To count spin, Count von Count must conjure imaginary bats.

The Count must also accept that these imaginary bats will always be imaginary and simultaneously have real-world consequences. Spin is very real and clearly affects experimental outcomes, but spin doesn't exist in a mathematical space that mirrors the physical space we know and move through on a daily basis. Spin only exists in Hilbert space. The same is true of the quantum state function. We can write down an equation that gives what we call "the wave function," which in turn gives us information about the probability that a particle will manifest in real space. That's all quantum equations guarantee us: a probability that something will happen. And that probability means extracting information about possible phenomena in the real world from Hilbert space, which isn't physical at all.

I know how unsatisfying this may feel to you. I've just given you a mathematical justification for why something is physically true. I also gave you a mathematical explanation that relies on an abstract idea and imaginary numbers that seem to have no physical correlate in the reality that we intuitively know. Is Hilbert space even "real" outside of our heads? What does it mean physically? Somehow the world emerges from abstraction into reality. We do seem able to write down equations that capture this, but we are unsure how the universe leaps from Hilbert space to our space-time or why. But as Michael Burnham (played by the wondrous Sonequa Martin-Green) says of *Alice's Adventures* in *Star Trek: Discovery,* "It's how I learned that the real world doesn't always adhere to logic. Sometimes down is up. Sometimes up is down."[5] In the case of quantum spin, sometimes particles are both spin-up and spin-down—a superposition of spin states. And sometimes the world can only be described using numbers that we can't physically intuit.

Our confrontation with abstraction might be confusing, but it can also be empowering. The late civil rights organizer and Algebra Project founder Robert P. Moses once wrote, "The Algebra Project is founded on the idea that the ongoing struggle for citizenship and equality for minority people is now linked to an issue of math and science literacy."[6] Importantly, he also insisted that building a movement around access to algebra education as a civil right was an important organizing opportunity that brought communities together and gave youth a voice in their future. "The Algebra Project is not about simply transferring a body of knowledge to children. It is about using that knowledge as a tool to a much larger end," he added. I encourage you to make your confrontation with spin—and with Hilbert space—a social experience. Tell someone about these ideas and how they affect how you see the world. Think about how you can use it to build community and hope and wonder too. Let your relationship with the universe and what questions you have about it be transformed by this knowledge.

Thanks to particles that spin without spinning, suddenly it seems natural to ask: If we are trying to tell a consistent mathematical story about the nature of the cosmos, how do we get from the uncertainty soup of quantum mechanics to a galaxy like our nearest major neighbor, Andromeda, which is always predictably exactly where we expect it to be? You'd think we know how to answer this literally enormous question. But we don't. Instead, these fundamental questions plague physics at its foundations, even as many physicists pretend they aren't a problem at all.

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* This is already true for theories that we might categorize as classical. Lawrence Sklar explains in his book *Space, Time, and Spacetime* that the traditional notion of geometry attributed to Euclid claimed to be entirely axiomatic but actually contained some unstated assumptions. In the Euclidean case, there are basic assumptions from which the rest of the geometric system should flow. There are also certain claims Euclid made within the system that can't be proven using those assumptions alone. So in a way, it is quite reasonable to consider that we have run into a similar problem when it comes to our sequence of Stern–Gerlach experiments.

Go to note reference *

* The epitaph on Hilbert's tombstone reads:
Wir müssen wissen.
Wir werden wissen.
(English translation: *We must know. / We shall know*.)

For some of us, curiosity is enough.

Go to note reference *

* For more on “imaginary numbers,” please read the mini-essay that is endnote number 4 for this chapter.

Go to note reference *

CHAPTER NINE

TRAP PHENOMENOLOGY

In which we wonder if the reality of quantum mechanics is a mockery of our sense of reality

> Alice laughed. "There's no use trying," she said: "one *can't* believe impossible things."
>
> "I daresay you haven't had much practice," said the Queen. "When I was your age, I always did it for half-anhour a day. Why, sometimes I've believed as many as six impossible things before breakfast."
>
> —Lewis Carroll, *Through the Looking-Glass*[1]

After I learned quantum mechanics, I never saw light the same way. All I could think was: *Photons, photons, photons! It's a wave of photon particles!* Impossible things had become my intellectual bread and butter.

Maybe it's weird to treat "light = discrete bits of matter" as a world-altering perspective. It's not like budding scientists aren't already familiar with discreteness. Those of us who come from communities with musical traditions that center drums know about the discreteness of the drumbeat—and also the complex ways that beats overlap, connect, and produce new patterns in the process. Each beat is its own, distinct entity, even when it works in conversation with others. The individual notes can independently invite us to nod, tap our feet, and create elaborate movement patterns in response.

We also hear the way this discreteness gets built into our cultural sensibilities. Consider trap music, a hip-hop music tradition that originates in the American South. In his book *Trap History: Atlanta Culture and the Global Impact of Trap Music,* A. R. Shaw explains that "trap music is more than 808 beats and lyrics; it is music that derives from a location."[2] The word "trap" in this context originally referred to the geography of drug hustles, to being in a situation where it was easy to get trapped both physically and metaphysically by the racist and painfully punitive war on drugs.

Beats in trap music are often characterized by a very specific halftime drum that identifiably forms a basis for songs that are created in the trap tradition. For example, Childish Gambino's song "This Is America" uses what *Pitchfork* called "the sharp contrast between jolly, syncretic melodies and menacing trap cadences" to highlight Black life under American white supremacy.[3] Part of the way the music works sonically is through sharp juxtapositions and trap beats that force the listener to notice the individual components while experiencing them blurring together into a distinct whole.[*]

Discrete rhythms are part of who we are, part of what makes us whole. Maybe if I hadn't been socialized into classical mechanics first, I could have sensed the rhythm of quantum mechanics, heard it as just another drumbeat calling out to me. Maybe I would not have had to unlearn what physics is supposed to do; what physics even *can* do.

Making Meaning of "Quantum"

Methodology is not a concept that humans are born with; it is a phenomenon created by communities. Rational knowledge production through a collection of frameworks that we broadly label "the scientific method" is a social concept that evolved over time. Historian James Poskett describes in his book *Horizons: The Global Origins of Modern Science* how Spanish conquistadores learned systematized approaches to data collection about the natural world from the Aztecs, whose empire covered the region that is now México. Poskett shows that traditional narratives about the scientific revolution and the creation of the "scientific method" are more mytho-hagiography than an accurate rendering of what actually happened.

The methods we use in physics have a social history, and quantum mechanics highlights for us the ways in which the science forces us to socially contest what shape it takes in any given moment. As I've described in earlier chapters, we have equations of motion that we'd like to solve in order to establish the state of the system. Quantum mechanics transforms this established methodology into something new. When we calculate in quantum mechanics, the equation of motion we solve is not actually an equation of motion that tells you directly how motion is occurring in a system. Even so, the phrase "equation of motion" continues to be the name we give to the equations that we would say define quantum calculations even though they no longer define deterministic information like where a cricketer's ball went after she hit it (see chapter 5 if your memory of this example feels fuzzy). The name "wave function"—which is what a quantum equation of motion defines—is both appropriate and misleading. It is potentially misleading because it might give someone the impression that it provides the description of a material object—let's say a particle—as a wave, when actually, on the face of it, the wave function is not a description of how the particle manifests. Rather, it describes a wave in the abstract sense.

The wave function, and the information it contains, corresponds to the probability of arriving at certain experimental results when an experiment is conducted with specific conditions. Instead of a guaranteed outcome like "The particle will be in Kilburn, London, on May Day," all we can do is say, "The expected value of the particle's location on May Day is Kilburn, London." What will happen is no longer certain—no longer entirely determined by initial conditions. In other words, the quantum perspective is the end of determinism in physics.

This is a big deal. In Newtonian physics, given initial conditions and/or boundary conditions and the right equations of motion, we could determine with 100 percent confidence the expected behavior of a physical system. Some people trace this viewpoint to our old friend Descartes, who took the position that the world had an order that followed unbreakable rules—what historian Helge Kragh summarizes as "mechanistic deterministic terms."[4] Descartes simultaneously believed in a supernatural Christian deity and also that the motions of heavenly objects were organized according to laws that the deity set in motion and did not interfere with.

Descartes is usually credited with the idea of a mechanistic universe. In a 1632 letter to Friar Marin Mersenne, he wrote, "Now I have become so rash as to seek the cause of the position of each fixed star. For although they seem very irregularly distributed in various places in the heavens, I do not doubt that there is a natural order among them which is regular and determinate."[5] Though this is often remembered and taught as a "Cartesian" worldview, Descartes was born only a few years after the death of Damascan-Ottoman polymath Taqi al-Din. In all likelihood, Descartes was familiar with al- Din's position that the universe was clocklike in nature. As Poskett shows, al-Din's ideas about clocks and the cosmos were "incredibly influential in Europe" and that al-Din went so far as seeking "to build a machine and a clock that would reflect the spiritual structure of the heavens."[6] Thus, a worldview that we have been assigning to Descartes may in fact not belong to him alone and likely does not reflect only a European Renaissance/feudalist perspective on the fundamental nature of the cosmos.

A New Sensibility

The fact that the mechanistic metaphor developed and gained traction signals that a key element of doing physics is interpreting how scientifically gathered information affects our worldview. Mechanism does have its attractions, but quantum mechanics challenges a physicist's trained sensibilities about what physics should and actually can do.

Should physicists be trained differently, so that we approach our work with sensibilities better tuned for quantum reality?[*] Perhaps. But first we would have to agree on what it is that physics does. Historian Joseph Martin has argued that "physics is what physicists decide it is."[7] In his book on quantum mechanics, Paul A. M. Dirac claims that physicists deal in observables:

> At this stage it becomes important to remember that science is concerned only with observable things and that we can observe an object only by letting it interact with some outside influence. An act of observation is thus necessarily accompanied by some disturbance of the object observed. We may define an object to be big when the disturbance accompanying our observation of it may be neglected, and small when the disturbance cannot be neglected.[8]

In other words, Dirac believed in a purely empirical perspective on science: A scientist's job is to deal in observations. And not just any observations but rather ones from controlled experiments in which we test and examine something by having it interact with an apparatus of our choosing. That is what I think of as a very physicist perspective on doing science: We can expect to create the experimental conditions ourselves. In astronomy and cosmology, on the other hand, we're often dealing with experiments that the universe is running whether we look at them or not, and we're just hoping to catch some photons or gravitational waves that give us insight into what the universe has done. Astronomers will never be able to force a neutron star and a black hole to collide; we can only watch it happen and try to understand from afar.[*]

Reflecting on the realities of astrophysical observation, quantum theorist John S. Bell had some choice words for the perspective advanced by Dirac. In his 1981 paper "Quantum Mechanics for Cosmologists," Bell quips:

> It would seem that the theory is exclusively concerned with "results of measurement" and has nothing to say about anything else. When the "system" in question is the whole world where is the "measurer" to be found? Inside, rather than outside, presumably. What exactly qualifies some subsystems to play this role? Was the world wave function waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer for some more highly qualified measurer—with a PhD?[9]

He goes on to say, "The concept of 'measurement' becomes so fuzzy on reflection that it is quite surprising to have it appearing in physical theory *at the most fundamental level*." Bell, who absolutely comes off like a bit of a queen, quite openly eschewed Dirac's emphasis on measurement, believing that there should be "concepts more *fundamental* than measurement."[10]

I love the way Leslie E. Ballentine talks about this in *Quantum Mechanics: A Modern Development*. Ballentine explains that "sometimes this mapping between physical and mathematical objects is so obvious that we need not think about it. In classical mechanics the position of a particle (physical concept) is mapped onto a real number or a set of real numbers (mathematical concept)."[11] This is one way of characterizing what is often called "intuitive" and "obvious"—like the way the numbers we use to count our fingers and toes correspond to the numbers we use to measure where something is. However, as you saw at the end of the last chapter, we need completely different numbers for quantum mechanics, and not a set of numbers that feels immediately obvious to us based on the systems we use in everyday life. Similarly, quantum-mechanical sensibilities about the "state" of a system are no longer so obvious as they are in classical mechanics.

It's useful, as Ballentine does, to make a distinction between the concepts of preparation and measurement. In the Stern–Gerlach experiment, the preparation would be the act of setting up the atomic heater and passing silver atoms through the magnet so that they interact with the target. The measurement is the act of observing the distribution of the particle impacts on the target. From this perspective, we can think about the probabilistic nature of quantum mechanics through the lens of what measurements we expect to get from any given preparation. In the classical world, a preparation corresponds to a single expected outcome (with some margin for error). In the quantum world, a preparation guarantees us an array of outcomes—states—with distinct probabilities of occurring.

Ballentine refuses to rely on our assumptions about what a state might be, explaining, "The concept of *state* is one of the most subtle and controversial concepts in quantum mechanics."[12] From his point of view, what physics aims to do is "give an objective realistic description of the world." I agree: A major goal in physics is to use measurements to extrapolate useful information about the world. Another is to develop theoretical models—representations of physical scenarios that capture the salient features—which accurately predict the outcomes of measurements.

Quantum mechanics taught me that physics should not be treated as acts of observation where we can pretend the observer isn't part of the physical system. And so, our view of what physics does—what it can do—has to change. Either classical physics is limited or our understanding of it is limited, and this challenges our sensibilities about what the practice of physics is. Physics, which is in part a science of predictions, is unpredictable. We never know where engaging in acts of physics will take us next. We are constantly on the edge of new information and a new understanding of what it means to do physics. The moment we think we have a fixed definition of physics, what we think is required to do physics shifts. Before the advent of quantum mechanics, physics was the study of particle-like matter. After? It's waves, all the way down.

Though Papa's brand-new quantum bag is exciting, it doesn't change our fundamental methodological commitment: to develop a sense of general principles or laws that govern how things happen, in such a way that they help us create stories with descriptive power. By descriptive power, I don't mean good prose (although that's helpful too); I mean that physics should create models of the real world that both help us characterize what matters about a physical system and enable us to gain insight into the fundamental workings of that system. This will empower us to make statements about the system's current state and possible future states, and to better understand why those outcomes are what they are rather than some other options. Dirac says, "It may be remarked that the main object of physical science is not the provision of pictures, but is the formulation of laws governing phenomena and the application of these laws to the discovery of new phenomena."[13] He then explains that when he uses the word "picture," he means "any way of looking at the fundamental laws which makes their self-consistency obvious." Dirac is describing a fundamental practice for the theoretical physicist in particular, a practice we now call "model building."

A model articulates the meaningful physical characteristics of a system or idea for a system. I think of models as living metaphors for aspects of the universe that we want to understand at their deepest, most fundamental level. It's helpful here to think about metaphor because, at the end of the day, that is an idea that works in a cultural context for us humans, in language that we have created. It's hard to know what a model for a specific phenomenon might look like if formulated by an alien species that is timeless and exists in a higher dimension, like the Prophets in *Star Trek: Deep Space Nine*. And our relationship to scientific metaphors can also shift with time; as we humans learn more, sometimes we dispense with metaphors that are not consistent with our changing understanding.

New ideas invite new, and sometimes terrifying, metaphors. For example, while trying to understand the concept of a superposition of states—where a system can be in two states at the same time—Erwin Schrödinger (accidentally) prefigured the Nazi gas chambers that would soon be used to murder millions across Europe. In his thought experiment, Schrödinger imagined a cat in a box where there is a chance that the cat will be exposed to toxic gas. There is also an equal chance that it won't be. There is no way to know what will happen until we observe the cat. Therefore, while it's in the box, the cat is apparently simultaneously both dead and alive—a superposition of possible forms that only becomes one or the other upon observation, just like Alice's mushroom.

This thought experiment raises an interesting question: How can a cat be both alive and dead at the same time? Sure, we can do calculations that are consistent with this interpretation of the equations, but what can that possibly mean, physically? In addition to the superposition of states, this feline thought experiment can help us visualize a deep conceptual difficulty in quantum mechanics that we also covered in the last few chapters—namely, the fact that the act of observing seems to determine what state matter is in. Because, surely, if the cat is plausibly in both states when the box is closed, it should still be in both states once the box is opened. But somehow it's only in one.

Living in a quantum universe means living with indeterminacy. Importantly, as Karen Barad explains in their work of feminism and quantum theory, *Meeting the Universe Halfway,* there was never universal agreement on how to interpret quantum indeterminacy. We know that Werner Heisenberg interpreted the mathematical uncertainty relation to mean that we cannot simultaneously *know* the position and momentum of a particle. Barad points out a less-discussed point of view, that of Niels Bohr—who, in Barad's interpretation, believed it was not possible for a particle to have simultaneously determinate values. Notice the distinction between Heisenberg and Bohr here: The difference is between interpreting a result as reflecting the observer's ignorance (Heisenberg) and believing that the information doesn't exist in the first place (Bohr).

Barad considers the implications for complex apparatuses—experimental setups—like people. Given that the preparation of an experimental apparatus can affect possible observable outcomes, Barad asks if it makes sense to consider state of mind as solely the (meta)physical "property of an individual." In other words, Barad interprets Bohr's translation of quantum indeterminacy to mean that:

> [T]he very notion of causality must be reconsidered, since the traditional conception—which presents only the binary options of free will and determinism—is flawed. But if causality is reworked, then power needs to be rethought. (Power relations cannot be understood as either determining or absent of constraints within a corral that merely limits the free choices of individuals.) Agency needs to be rethought. Ethics needs to be rethought. Science needs to be rethought. Indeed, taking Bohr's interpretation seriously calls for a reworking of the very terms of the question about the relationship between science and ethics.[14]

But wait, you might be thinking. Hold on! When reading about the Stern–Gerlach experiment, I just wanted to know where a silver atom would land on a target after flying through a magnetic field. How did we get from there to questioning the relationship between science and ethics? We land here because of the way measurement in quantum mechanics escapes easy or even rational interpretation, especially in relation to time (something I'll discuss in detail in the next chapter).

The determinism of Newtonian physics came with the promise that we can choose the future with certainty. Given sufficient control over physical conditions, we can determine the outcome. Quantum physics alters this feature of our reality, which raises questions about our agency. We can choose the array of possible options—and their likelihoods—b ut we cannot make guarantees anymore. It is perhaps not necessary but also perfectly reasonable to think through what it means to make ethical assessments, given this transformation of the context in which we make them.

You might think this means that quantum mechanics has no rules, but it does—it's just a very different set of rules from the ones we might arrive at when thinking about the size and distance scales of everyday life. Quantum mechanics has boundaries on what is possible and what isn't, but these are quite different from the boundaries we are used to. If we know the wave function of a system, we know how that wave function will evolve over time. There is a clear rule governing this. The wave function contains information about the possible measurable physical scenarios a system might be in. What it usually doesn't tell us is which scenario it will, for sure, be in—it only gives us the likelihood of it being in one or the other. This forces us into a different way of thinking about the relationship between prediction and measurement, one distinct from how classical physics encourages us to think about it.

The Only Way Out of a Paradox Is to Live with Another

So. Quantum mechanics will fuck you up. And we start to see why Bell was so appalled by the emphasis physicists placed on measurement. Think about how the Stern–Gerlach experiment was put together: Gerlach assumed that he could connect the experimental apparatus in a deterministic manner. No quantum mechanics went into the preparation of the experiment, which was in fact designed to knock down a proposed quantum idea. The apparatus as imagined by Gerlach was a classical phenomenon, and to this day, we still do experiments with this mindset even though we know everything is fundamentally quantum. But somehow this hasn't been a problem—we still get results that are quantum in nature. In other words, the experimental apparatus's existence appears by all accounts to be deterministic, but the results it produces are probabilistic.

It's easy to say that, here, size might matter: The apparatus is big and the particles are small. But the apparatus is made of particles. Is there a scale that acts as a boundary between "behaves classically" and "behaves quantum-mechanically"? Trying to make sense of this bizarre juxtaposition where the observe*r* is classical but the observe*d* is quantum is known as the measurement problem.

Another way to think about the measurement problem is through the question of superposition. We don't measure individual particles in a superposition of states—we measure a definite outcome. Dead *or* alive, not dead *and* alive. So in the scenario where we have a system that is prepared in a superposition of states, how does it "choose" which one to be in when we take a measurement? Disagreements about how to resolve this abound. There is the camp that says that this is a fake problem, born of human ignorance about the correct theory of reality—in other words, our knowledge is incomplete.

Einstein is one of the most famous champions of this perspective: He, along with Boris Podolsky and Nathan Rosen, published a paper in 1935 entitled "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" EPR, as the paper is known to physicists, defines "complete" to mean that "every element of physical reality must have a counterpart in the physical theory."[15] EPR is concerned with the conflict between this idea and the Heisenberg uncertainty principle, the idea that a particle's position and momentum cannot be simultaneously exactly measured.

The thought experiment considers a state preparation where there are two particles initially interacting, making their quantum state linked. Then they move away from each other in opposite directions, so they no longer have any interaction, although their relative distance from each other is known. The position of particle A is then measured, which presumably does not involve the measurement system interacting with particle B. Therefore, the position of particle B is calculable without disturbing it through direct observation, even though A has been disturbed by measurement. According to EPR, being able to measure this property without interacting with B makes the position of B an element of physical reality.

EPR also point out that they could instead measure the momentum of A and then calculate the momentum of B, implying that the momentum of B is an element of physical reality. In other words, the position and momentum of B both seem to be elements of physical reality, even though neither is directly measured in this scenario. They have both been definitively measured. EPR argued that particle B has predetermined physical properties that are unchanging and not dependent on observation—suggesting that these properties are classical, not quantum, in nature. But the particle started, by definition, as part of a quantum system. This is the EPR paradox.

EPR created this paradox for the purpose of showing that quantum mechanics is an incomplete description of reality. The experiment appears to show that it is possible to measure a particle's position and momentum simultaneously, even though a quantum wave function does not contain this information. This suggests that the wave function's information must be incomplete. An additional consideration here is that it's not possible for particle A to instantaneously affect particle B, which Einstein referred to as "spooky action at a distance." We've met action at a distance before—both gravity and electromagnetism working across arbitrary distances—and concluded that there has to be some kind of mediating phenomenon, like a field. The fastest information can travel in a field is at the speed of light, so instantaneous action at a distance is a big no-no.

EPR insisted that their hypothetical system should respect this rule, so all physical interactions had to be local—close enough for information to be exchanged as if the particles were neighbors, rather than distant colleagues. Their conclusion? Since it's possible to get classical, predetermined measurements, there must be some other characteristics at work that make the apparently quantum system deterministic. We just don't know what those characteristics are (yet) because they are hidden. From the point of view of EPR, this was a better explanation than the idea that quantum effects could be nonlocal, that measurements of particle A could affect the properties of particle B via spooky action at a distance.

Where EPR saw a problem, Bell saw an opportunity. He proposed a theorem to be tested: Quantum mechanics could not be entirely described by a theory that has hidden characteristics like the ones EPR needed to explain away their paradox. Since the 1980s, all experiments seeking to test Bell's theorem have shown that it is correct. The idea of hidden characteristics doesn't seem to manifest in experimental data. And while this might sound like a disappointment, it comes with an exciting by-product: the prospect of observing entanglement.

Entanglement is the one known plausible way to sidestep the limitations presented by the finite speed of light without doing anything strange to space-time. Consider two particles that are in a pair, one spin-up and one spin-down. We separate the two and measure the spin of one of them. It turns out that measuring the spin of one will tell us the spin of the other. In other words, the particles are entangled in a shared state, even when they are no longer local to each other. I know this sounds absolutely wild, but it's also something that has been tested repeatedly—at long distances, to boot.

As early as 1949, Chinese American physicist Chien-Shiung Wu established that entanglement occurred with photons. Experiments with entanglement build on her legacy. In 2018, my former postdoctoral advisors at MIT, Alan Guth and David Kaiser, my onetime Harvard classmate Andrew Friedman ז״ל, as well as Anton Zeilinger's research group and Jason

Gallicchio, tested entanglement with the help of highly energetic galaxies known as quasars.[16] In this experiment, they used photons from the quasars to help them set up the entanglement experiment and search for evidence of hidden variables. They found none.

The failure of hidden variables in that scenario suggests that we must look to other ways of interpreting how measurement works in quantum mechanics. The Copenhagen Interpretation—to "shut up and calculate," as N. David Mermin apparently put it—is the approach most of us are taught to take. In this approach, we just have to accept that observation causes the wave function to "collapse"—and that there is a true separation between a classical experimental setup and the quantum phenomena it measures—leading to the value we ultimately observe.

Another interpretation that has had quite a bit of cultural purchase is Hugh Everett's many-worlds framework, which suggests that all possible outcomes do happen in realities that are constantly branching off from each other. In this scenario, there is a universe where the cat is dead and a universe where the cat is alive. When we open the box, we find out which universe we live in. Another way of thinking about it is that with each decision we make, new universes are created, full of possible next moments. This suggests that rather than a universe, we live in our very own iteration of the universe—a small part of a dazzlingly complex and potentially infinite multiverse.

The way that the many-worlds interpretation has become a popular concept in pop culture is a great example of the unexpected ways that our big scientific questions become cultural drivers. You'll find it at the heart of the Marvel Cinematic Universe and the mirrorverse concept in the *Star Trek* franchise. I think the most creative and faithful interpretation of the many-worlds framework can be seen in the Daniel Kwan and Daniel Scheinert–directed film *Everything Everywhere All at Once*. The movie stars a brilliant Michelle Yeoh as a harried working-class Chinese immigrant and mother, Evelyn, who is struggling to juggle her financial and marital problems and to treat her lesbian, American-born daughter Joy (played by rising star Stephanie Hsu) with dignity. The absurdist, surrealist science- fictional narrative hinges on a creative interpretation of many-worlds to construct an allegory for the pain caused by parents who misunderstand, mistreat, and reject their queer children. In order to save her daughter from complete destruction, Evelyn must experience all possible versions of herself, across all possible timelines—including one where she is also a lesbian—to learn how to better love her daughter. She experiences these different versions of the world first in parallel, and then simultaneously.

The universe-expanding concept of many-worlds is not the only new idea that quantum mechanics invites us to consider. Karen Barad has advanced the concept of “agential realism” as a new way of thinking about the relationship between the observer and the observed.[17] This interpretation is based on a close reading and creative extension of Niels Bohr’s ideas. Agential realism takes seriously the idea that the observer is part of the experimental apparatus, not separate from it—Barad proposes that phenomena are emergent from apparatuses through what they call “intra-actions” between observers and objects. By extension, they also argue that quantum mechanics makes more natural the idea that science and scientific ethics are inseparable. Barad’s book, which I recommend you check out, argues that quantum mechanics means our moral decisions are part of the scientific system.

TRAP Phenomenology

John Bell was pretty peeved about the elaborate explanations scientists kept coming up with to deal with the interpretation problems raised by quantum mechanics—which may not even be real problems. Quantum mechanics is incredibly successful as a theoretical framework—derived from the advanced mathematics of linear algebra—that allows us to determine what experimental outcomes we should expect. But Bell felt this was insufficient, and with an enormous amount of shade referred to this approach as “JUST FINE FOR ALL PRACTICAL PURPOSES” (FAPP), since it leaves a lot open to interpretation.[18] Just before his death in 1990, Bell worried that physicists were not serious enough about solving what he saw as the problem of quantum mechanics. He was concerned that physicists, too enchanted with our functional FAPP “phenomenology”—the qualitative story we were telling ourselves based on our data—were forgetting that the goal isn’t simply to be able to calculate correctly but also to actually describe the world.

With this in mind, let's revisit the double-slit experiment described in chapter 7, which seems to show that electrons are both particles and waves. This experiment is often popularized as definitive proof that at the smallest scales, a quantum description is necessary to explain measurements. The experiment highlights three phenomena: First, the outcome shows that electrons behave like a wave and a particle simultaneously. Second, the experiment setup shows that a particle's behavior depends on whether we engage in the act of observing it or not. Third, and perhaps most jarringly, these outcomes *also* imply that particles don't exist until we observe them. But as Bell pointed out, this sounds ridiculous.

One option is to not worry about what all this means. All physicists learn to calculate using the mathematical framework of quantum mechanics, but that doesn't mean we can actually explain what it means or how to interpret superpositions, wave-particle duality, and the fact of probabilistic rather than deterministic outcomes. In fact, we physicists are rarely encouraged to think very deeply about what it could mean. If we go far enough in our education, we get the opportunity to see just how accurately these calculations align with experimental results, so we learn to trust that the calculations are correctly describing reality.

Another option is to consider whether we are wrong to think that classical mechanics simply doesn't have the capacity to explain quantum phenomena. In a 2021 research paper, Lorenzo Catani, Mat-thew Leifer, David Schmid, and Robert W. Spekkens name the three developments—wave-particle duality for light, wave-particle duality for particles, and quantum indeterminacy—that are "traditionally regarded as problematic," or TRAP.[19] TRAP phenomenology forms the basis for our arguments that quantum mechanics is necessary. *We simply cannot explain the phenomena using classical physics,* we tell ourselves, our students, and intrepid readers of publications like this book. Too often, the response to the quandary of TRAP phenomenology is to shrug and say, "Well, it works for all practical purposes."

Bell felt that TRAP phenomenology could become FAPP complacency. But just as trap music invites us to rethink our cultural norms around poverty, criminalization of drug use, and the power of rap music, perhaps TRAP phenomenology can invite us to reinvent rather than supersede classical mechanics. As Catani, Leifer, Schmid, and Spekkens point out, our inability to use classical physics to explain TRAP phenomenology might be a human failing, not proof that the universe is more complex than Newton imagined. In their paper, which is currently the subject of active debate, they develop a classical theory that can describe TRAP phenomenology without reference to the quantum framework.

To be clear, the goal of this research team isn't to convince us that quantum mechanics is a bad theory. Instead, they want scientists to do better when it comes to proving the claims we make about how the universe works. Rather than simply arguing that experiments displaying apparent quantum behaviors require us to move to a quantum-theory framework, scientists should prove that it is absolutely impossible to develop a theoretical framework using only classical ideas. Otherwise, we leave open the possibility that in fact, as John Bell suggested, the lack of a classical explanation is not a failure of the classical laws of physics but rather a failure of imagination by theoretical physicists. The Catani team have raised a point that I had never considered until I read their paper: Are the boundaries we imagine for classical physics simply failures of imagination? If those boundaries are real, then we should be able to prove that a quantum framework is necessary.

Do I feel less compelled by quantum mechanics in the absence of this proof? Not particularly, because I've got the Stern–Gerlach experiment to keep me warm at night. But I didn't always feel this way. I spent much of my career not giving any thought to the Stern– Gerlach experiment. I have zero recollection of ever seeing any discussion about it in class—although maybe that's because during the semester I took intro to quantum mechanics, I spent a month involved with a sit-in and tent city protesting the low wages of Harvard workers. I didn't really think much about the Stern–Gerlach experiment until I was tasked with teaching graduate-level quantum mechanics. Once I spent some time reading about it, however, I became obsessed: I spent two months preparing one lecture on the topic. It was too much fun—here was an experiment whose results force us to shift our thinking; to accept that beneath the familiar façade of objects governed by Newtonian mechanics, there is a quantum world lurking and behaving in a manner so unnerving to physicists that, for the last century, whole swaths of the community have been arguing about whether the word "measurement" is a bad word.

I used to tell people that some questions in physics, like the meaning of quantum mechanics, veer into the realm of philosophy. Those questions are for people smarter than me, I said, or at least people more keyed into questions of meaning rather than the questions of prediction that interested me. But then one day, I started to think about the Stern–Gerlach experiment, and I've never been able to stop. The implications for the world, the ways it leads us to realize that the world we thought we knew isn't what we thought it was, are deeply compelling.

The Stern–Gerlach experiment absolutely ruined me. I am now one of those physicists who thinks that the problem of quantum mechanics is not at all (solely) a question of philosophy. I believe in the possibility that it's a question of the physicist's failed literary imagination. Perhaps we have simply been unable to find the words, either in spoken language or mathematical language, to describe what quantum mechanics teaches us about reality. I have also been witness to the way an honest confrontation with these questions changed me and my relationship with the world. Perhaps you are experiencing a bit of that too.

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[*] I owe a debt of gratitude to Jessie Cox's *Sounds of Black Switzerland: Blackness, Music, and Unthought Voices,* which helped me think this through.

Go to note reference *

[*] I especially recommend the books on the history of quantum mechanics by David Kaiser, Anil Ananthaswamy, and Adam Becker. They are filled with discussions about these types of questions.

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[*] Black studies theorist and historian Lisa Alexander pointed out to me that in this sense, it's a lot like being a cultural critic.

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CHAPTER TEN

QUANTUM SANKOFA

In which we accept that we now have a quantum history problem

> . . . nor did Alice think it so *very* much out of the way to hear the Rabbit say to itself “Oh dear! Oh dear! I shall be too late.”
>
> —Lewis Carroll, *Alice’s Adventures in Wonderland*[1]

> There are some enterprises in which a careful disorderliness is the true method.
>
> —Herman Melville, *Moby-Dick; Or, the Whale*[2]

Chaos, Control

The power and problem of time were imprinted on my brain by T. S. Eliot’s “Burnt Norton,” the first poem I read in a collection my father gave me for my twelfth birthday. Since then, Eliot has become one of my problematic faves, a snob who was both an anglophile and something of an antisemite. Even so, when my (Jewish) father introduced me to his poetry, I immediately became obsessed with the way Eliot used words to give conceptual shape to the physical world. “Burnt Norton” is a meditation on the nature of time, both as a human experience and a physical concept:

> Time present and time past
> Are both perhaps present in time future,

And time future contained in time past.
If all time is eternally present
All time is unredeemable.
What might have been is an abstraction
Remaining a perpetual possibility
Only in a world of speculation.
What might have been and what has been
Point to one end, which is always present.[3]

The opening is a literal statement about the relationship between "time present," "time past," and "time future." The entire composition is both a metaphor for how we humans understand our relationship to time and also how time works in the universe, written during the 1930s, when human sensibilities about the physical nature of time were undergoing dramatic transformations.

The year that Eliot wrote "Burnt Norton," special relativity turned thirty and general relativity turned twenty. These ideas were still relatively young, circulating in an era when mass communication was not nearly as instantaneous as it is now. At the same time, as is obvious from Eliot contemporary Robert Frost's comments about metaphors, both general relativity and the evolving theory of quantum mechanics were beginning to reshape literary sensibilities about the basic composition of reality. As with space, the literary conversation about time is a kind of nature writing that is rarely recognized as such because time and space are so ubiquitous, and because our relationship with it does not always feel terribly natural.

Even so, our personal sense of time feels innately physical. Consider how it is portrayed in Christopher Nolan's movies, which are almost exclusively about time, in one way or another. I can't fault him for being so obsessed with the concept; there's so much material there. Perhaps the most famous example of Nolan's time play is the 2002 film *Memento,* in which a man, whose short-term memory is dysfunctional, hunts down his wife's murderer. In the film, the viewer gets to do something that we can never do in real life: be a detached observer outside of time. While lead character Leonard Shelby is ostensibly moving forward in time, the plot essentially runs in the reverse direction. The movie, which ends with the audience landing at Shelby's beginning, highlights the fact that short-term memory is key to our conscious experience of the arrow of time. This playing with time is especially effective, in a storytelling sense, because Shelby's dysfunctional memory means that he essentially has no concept of the past.

Having read that, I hope that you stopped and wondered whether "the arrow of time" exists outside of our observations. And I hope that your inner John Bell then immediately popped up, much like Queen in the epic music video for "Bohemian Rhapsody," shouting that you need to let go of the idea that the rest of the universe was just waiting for you to be born and look at it. But while there's no doubt the universe exists with or without people to look at it, I understand why it's so easy to focus on how our experiences and observations of time shape our own personal lives.

There is a political element to this: A few years ago, NPR science reporter Geoff Brumfiel reached out to me for a story he was working on about how physicists think about time. I was delighted when he published one particular comment I made: "Capitalism sucks, and I think a lot of people's relationship to why time is not cool, is structured by the resource pressures that we feel."[4] Living in a society organized around neoliberal ideas about the supreme importance of market growth and productivity means that we often feel our lives are governed by an oppressive form of timekeeping. There's also the way our own bodies and built environments seem to function as visual examples of time ticking away—certainly my hair seems to know about time, as it becomes increasingly melanin-challenged and experiences texture changes. The passage of time from the past into the future, with a short stop at each instantaneous present, feels so intuitive that it's natural to imagine that its physical nature is likewise obvious.

Our sensibilities about time are also intimately connected to our socialized understanding of our history. As Dipesh Chakrabarty points out in *Provincializing Europe,* European notions about history construct an idea of time that is "continuous, and to follow [Walter] Benjamin, empty and homogeneous."[5] Because history is understood to have a linear trajectory, time is understood to follow the same path. Chakrabarty notices that this sense of time is "godless," but I'm not sure I agree. Christian conceptions of a god always seem to hover over the evolution of scientific ideas in the Western world, including ideas about time. This is an inheritance. Muslim scientists are largely responsible for the development of European astronomy, for reasons somewhat related to the importance of accurately calculating prayer times. Earlier, I mentioned the astronomer Taqi al-Din, who was enthralled by the European clocks he came into contact with and connected them with an early cosmological mechanism. Al-Din, you'll recall, also wondered whether the universe was a machine akin to a clock. This is perhaps the earliest metaphor in physical cosmology. I can understand why this is an attractive point of view, especially for someone raised in a mechanistic society, as most of us are—b y which I mean we belong to a society organized around the idea that everything follows an orderly set of rules and patterns.

If we return to the Zhou kingdom or the early days of Enlightenment Europe, we see that intellectuals were grappling with the idea that space, time, and material objects were governed by rules that could be clearly stated and consistently applied. Muslim astronomers across western Asia, the Middle East, and Africa created an extraordinary body of science rooted in this premise: Astronomical bodies followed specific rules, and their motions could be predicted with a high degree of accuracy. They were given the resources to do this in part because they were tasked with ensuring their royal leaders knew the four daily prayer times that depended on the sun's location and when important festivals like Eid arrived. It's clear from the historical record that it has long been and continues to be a central Muslim tradition to value rational knowledge production about the world as a way of honoring spiritual commitments.

Working to translate our lived and spiritual sensibilities into physical theory is a quite rational and often powerful impulse. Indeed, the sun does have very clear patterns, as do the other planets in the solar system. And the patterns can be explained by Newtonian mechanics and relativity. But if we were to zoom in to a small enough scale, we would find ourselves among phenomena that are inescapably beyond Newtonian rules, governed instead by the laws of the quantum realm. The quantum realm, as you now know, is a land of indeterminacy. There, the promise of knowing for certain where any given particle will be disappears.

Like the mythical two-sided Wassily Kandinsky painting featured in the film *Six Degrees of Separation,* dubbed "chaos" and "control" by Stockard Channing's incredibly memorable Ouisa Kittredge, we live in a world that seems to be governed by quantum mechanics while classical mechanics is what eventually emerges. Now is a good time to ask: How could the apparently classical, large-scale universe we know about possibly emerge from the messy realm of quantum mechanics? This question isn't just about space; it's also about time. The universe is permanently full of uncertainty, incompatible observables, fields that are everywhere, and so on, but also there is a clear arrow of time that governs causality in both classical mechanics *and* quantum mechanics.

Newton thought defining time was pretty straightforward, giving a definition alongside the concept of "absolute space" that I discussed earlier: Absolute, true, and mathematical time, in and of itself and of its own nature, without reference to anything external, flows uniformly and by another name is called duration.[6]

You already know that this is on the list of ways in which Newton was, as my Bajan mom would say, wrong and strong about it. He was quite confident, for reasons that elude me. But I suppose many people who were likewise invested in enslavement were also overly confident about their worldview; their ability to determine what is right and what is wrong. As attractive as it is to define time as absolute, like Newton did, the idea simply doesn't hold up once we know something about electromagnetism and/or the speed of light. The discovery of quantum phenomena also forces us to revise: If the outcomes are probabilistic, how can we be certain of what it means for "time future to contain time past"? Which time past are we even talking about?

But there's also the question of "which now?" Relativity makes clear that time is relative, and this shifts our understanding of simultaneity. Depending on our relative motion, we may not agree about what time it is. In the context of space-time, all events simply exist in different locations in space-time. As Einstein once quipped in a letter to the family of engineer Michele Besso, "For people like us who believe in physics, the separation between past, present and future has only the importance of an admittedly tenacious illusion."[7]

Orienting Ourselves

Relativity forecloses on the idea of absolute time. But even in the context of relativity, time has a special position that affects what trajectories—pathways—in space-time are plausible. We do have to be attentive to the idea of causality, the principle that effect always comes after cause.

In spatial dimensions, we can move in any direction. With time, there is only one direction. Even in the context of relativity, where we understand space and time as not entirely separate, there is still a concept of a dimension where we only ever move forward. Thankfully, the equations always have a sense of a single time dimension and three spatial dimensions. The only things we might debate are how fast time is flowing and how much distance has been covered by an object in motion. But space-time is oriented.

Remember that in chapter 5, I wrote about Sara Ahmed's notion of what it means to be "orientated" and for bodies to take up space and time. One can read this as a matter of social analysis, but the fact is that the idea of sexual orientation emerges from us—humans—and we emerge from particles that are governed by quantum mechanics. To take the analysis to its logical conclusion, to ask what it means to be "orientated" can mean to ask how sexual orientation emerges. In physics, we also have a concept of orientation; for example, in ferromagnets, the most common kind of magnet, the magnetic poles of the atoms are all *oriented* the same way, creating a macroscopic magnetic effect. Remember that when quantum spin is involved, this orientation isn't in physical space; it exists in an abstract sense and is described mathematically as occurring in Hilbert space. But the orientation still has implications for what happens in physical space: It leads to spontaneous magnetization, which we can see and observe. Somehow, some quantum abstractions emerge from an abstract mathematical space that doesn't map onto the space of everyday life—and leap into the real world of our everyday lives.

Let's keep going: Physical objects are here; they exist in space and time. I can move many physical things in any direction in space. But I can't change the direction of their movement in time, and the only way to change the pace that time flows for them is to use lots of energy and make them go near the speed of light.

Even so, *time-reversal symmetry* is a fairly important principle in physical theories. We expect that any law we write down will be true even if we flip the time coordinate—the marker of time—and roll it backward. This is different from the observer going backward; it is more like being able to reverse-engineer. Let's go back to the Missy Elliott song "Work It," which I discussed in chapter 5. We can think of each line as the other line in reverse order: "*I put my thing down, flip it and reverse it*" follows an arrow of time forward. Time-reversal symmetry means that Missy can reverse the sequence of the words, leading to the subsequent line, "*Ti esrever dna ti pilf, nwod gniht ym tup I*," and if I reverse the time order that we hear it in, it will sound the same. Similarly, when Dodgers stars Mookie Betts and Shohei Ohtani hit home runs, we could roll back the tape and watch the ball go back into the field of play and eventually back to the point of collision with the bat, and no laws of physics are violated by this. The physics of the ball moving through the air remain the same, whether time is moving forward or we are looking at it backward.

Yet we never see the ball go backward to the bat. And many of us who grew up trying to keep up with the lyrics to Elliott's "Work It" probably murmured something like "*yer frimonipiphwad yad cudup*." (Or, at least that's what I was doing.) It's hard to undo what has been done, even in scenarios where we actually can go backward, like saying the letters in the reverse order. If I break an egg, in principle all the pieces are still there, but it's pretty hard to restore it to its previous condition. Even if I can glue the shell back together, if the yolk is broken, there is no mechanism that I know of to restore the yolk to its previous condition.

We are forced to reckon with the arrow of time in so many different ways. The laws of physics may be symmetric with respect to time, but that doesn't mean time is itself reversible. But what makes restoring the egg so difficult? Well, a broken egg has become irreversibly messier and more disordered. And it turns out that in physics, we have a technical concept that roughly characterizes disorder: entropy.[*]

Aging with Complexity

Technically speaking, entropy is a count of the number of different ways that a physical situation can be arrived at. I could break an egg in a lot of different ways and end up with the same mess of broken shell and yolk mixed with egg white. But there's pretty much only one way (for now—talk to my colleagues in biology, I guess) to make an egg.

Another example of how entropy works is this book itself, and I don't just mean because writing it was complete chaos. If I were to create a code that randomly scrambled all the words in the manuscript, there are more than 110,000!—110,000 factorial, which is the largest number I've ever seen, 5.27 x 10^{506783}—different ways this book could be written.[*] Such a mess of disordered words is a high-entropy scenario. But there's only one way to write it exactly the way it ended up being written—that's a low-entropy situation. In reality, it's hard work to write a book in order; it would have been easier to type random words until I got to the rough number of words I told my publisher I would write. In other words, the high-entropy scenario is easier to achieve. And again, if I were to write an algorithm to randomly organize the words in the software I use to write (Scrivener), there are lots of different ways to arrive at total gibberish and only one way to arrive at the book I actually wrote. On the other hand, if the book were only ten words, there would be a higher chance of randomly stumbling into all the words in the correct order. The higher word count increases the possibility of the book evolving into a state with higher entropy.

All of this is really a metaphor for the second law of thermodynamics, which states that in isolated physical systems with a lot of elements, entropy never decreases and is likely to increase. Entropy grows over time. Maybe you see where I am going with this—entropy gives us a concept of a phenomenon that provides a naturally emerging sense of direction, a sense that seems to point in the same direction as time. When we have objects comprised of many elements—like a person or a roof—the second law applies and seems to indicate that the forward arrow of time emerges from their composition of many elements. Roughly speaking, this means that as time goes on, things tend to get more disorganized and chaotic.

But this isn't a complete explanation of the arrow of time. As scientists love to point out, correlation does not equal causation. Sure, entropy grows with time, but does that somehow innately relate to the *direction* of the arrow of time, or is it just a side effect of it? The tendency among physicists who spend their time (if you will) on the origins of time—and that's very few of us, because it's hard to get paid for it—is to believe that the second law of thermodynamics is an important hint about time's origin. Once we accept this premise, the refined question that remains is how the tendency of entropy to increase over time *orients* time in one direction, despite the fact that the laws of physics tend to be time-reversal symmetric.

The fact that we don't know what we're doing yet isn't worrisome. More concerning is how we are approaching the problem. We have a tendency to apply the second law of thermodynamics to the entire universe, but the boundary conditions of the derivation for it are actually for an *isolated* system in an *unchanging* space-time. Embedded in this setup is the suggestion that the observer is external to the system, not inside of it. But we know the truth: On cosmological scales, space- time is expanding, changing, moment to moment. Also, we're inside the universe, not looking at it from the outside like the aliens playing with marbles at the end of the film *Men in Black*. And you already know what John Bell had to say about the foolishness of assuming we are outside the system or that we are special observers. There is no way to look at the universe from the outside. So while there is good reason to believe that the second law applies even on small scales where cosmological expansion doesn't matter, there is also good reason to question whether it applies to the universe as a whole.

To me, this certainly feels like a truly significant, deeply troubling problem. But you wouldn't know it from asking most physicists what they think the most pressing challenges of our time are. The culprit here is a mix of capitalism and utilitarianism: Everything we do is expected to have obvious value. But remember one of our first lessons: An education in symbol and metaphor is the only way to be safe in science. Even so, the orientation toward making "useful things" means that few physicists devote much time to the teaching and study of the science of time. It's not a topic that's covered in any undergraduate curriculum that I've ever seen. Instead, it's taught and utilized as a parameter, a marker against which change is measured.

I think one of the most memorable contemporary thinkers on this subject is theoretical physicist Julian Barbour, who has coincidentally made a living *not* as a physicist but rather as a Russian-to-English translator. Barbour comes from a community of physicists who are committed to thinking about the most fundamental questions—a group of scientists who help the rest of us keep things in perspective. Barbour and a variety of collaborators—including Tim Koslowski, Flavio Mercati, and David Sloan—

have suggested that we rethink how we conceive of the origins of space-time, as well as how it evolves. There are two primary adjustments to our perspective that they invite us to make. The first is that we start to think of the singularity at the edge of our cosmic timeline, the Big Bang, as a special point in space- time—but not the beginning. Instead, we should imagine it as a point where the size of the universe is at a minimum; which is to say that on either side of this point, the universe's size grows. Barbour calls this the Janus point, so named for the two-faced Roman god (see Figure 10.1).

The other adjustment they suggest we make is to understand that, rather than evolving toward chaos, the universe evolves toward complexity. In *The Janus Point,* Barbour points out: "One can argue . . . That the time-capsule nature of the universe—the way its state now proclaims a past history of growing complexity with extraordinary internal consistency—is the single most striking empirical fact that calls for scientific explanation."[8] In other words, the fact that the universe tended toward the creation of matter in complex dynamical forms—planets, stars, galaxies, and galaxy clusters, to name examples in order of mass and length scales—suggests that complexity, not chaos, should be the guiding concept.

Figure 10.1. The Janus god, for whom the month January is named, has two faces: a sad one and a happy one, representing war and peace, respectively.

To capture this new conception of our evolving space-time, Barbour names a new concept, *entaxy,* a notion akin to entropy but more appropriate for what he calls "an unboxed universe." While entaxy has some conceptual overlap with entropy, it works a bit differently. In the framework proposed by Barbour and his colleagues, the key feature entaxy captures is that the universe isn't tending toward chaos but is instead tending toward complexity. They believe that this can be consistent with the second law of thermodynamics, since cosmological entaxy does not prevent entropy from increasing in smaller systems that are inside of the universe. Instead, entaxy defines a cosmological tendency that is a feature of space-time—and the evolution of complex structures then becomes a by-product of the arrow of time's embedding in space-time itself. Perhaps the universe's true method is a careful disorderliness, complexity.

While introducing these ideas, Barbour makes an interesting historical note about why it is valuable to think about this question and how this solution is in line with that value. He points out that Ernst Mach (for whom the sound speed units are named) argued that we understand science better when we take the time to understand ideas in the context of their discovery—Mach believed that the history of science was an integral part of science. Barbour agrees: "the history matters." This urges us to return to Robert Frost: We are not safe in science if we do not know our history, and we will not know our science if we do not study its past.

Go Back and Get Many Histories

The idea that entanglement is possible looms large over the question of what it means to do cosmic history. As you know by now, quantum mechanics is an ever-present complication—two particles, both alike in nature, can then be separated by large distances and still apparently remain in a shared quantum state. These particles don't need to reach backward in time or forward to hold on to what is theirs. It is, apparently, an instantaneous and inseverable link. This adds a whole new meaning to the call to *Sankofa,* to go back and get our cosmic history.

At the same time, we are dealing with a world of probabilities, where it may be impossible to deterministically predict the future, even for a particle. And this, too, raises interesting questions about the past. Let's revisit the double-slit experiment with electrons yet again. If you were thinking about them like little tennis balls being hit by tennis champion Coco Gauff, who has incredible control over her ball placement on the court, you expect them all to go through one slit or the other. But we now know that they will behave like waves, and we will see an interference pattern that reflects this. One way of thinking about what's going on here is that the electron waves are behaving like they have gone through both slits—like a classical light wave would.

This experiment might not seem like it has much to do with time, but in fact this is a big statement about the electron's past. Usually, the deterministic story we want to tell about a group of electrons is that they began at their point of origin, were sent on a journey toward the two slits, and then each electron went through one slit and was detected on the other side. But now we have a situation where they apparently went through both slits. This suggests that each electron has two histories. Which one is the "real" one? Is there only one real one? How can the electron go back and get its past?

One interpretation of what is happening is in fact embedded in a quantum calculational technique known as sum over histories. Using this technique, we assume that all possible trajectories did occur, as modeled in Figure 10.2. The probabilities associated with each one will be encoded in dynamical information we have about the energy structure of the system. Then, using this information, we can calculate the likelihood of an object being at point A or point B.

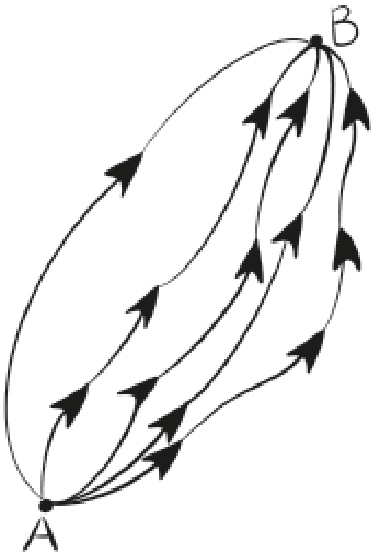

Figure 10.2. Different possible paths from point A to point B.

There are people who have taken this feature of quantum mechanics and what it suggests about past histories quite seriously. In his book *The Origin of Time,* Thomas Hertog explains the work he and Stephen Hawking did together on a theory attempting to understand the Big Bang through the lens of working backward in time over a sum of quantum histories. This is a radical idea that has not received widespread acceptance in the physics community, but it is nonetheless interesting to consider how a quantum notion of the present must dramatically transform our understanding of the past, and what it even means for the arrow of time to march forward.

Perhaps going back to the early cosmic past and getting it is a multiplicity of quantum leaps that can take us to many different possible pasts. Maybe there's one where my ancestors left a place like the mythical Marvel Comics land of Wakanda, departing as curious travelers rather than kidnap victims from the Gold Coast of Africa.

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[*] Here's a funny story. In 2021, I published a book called *The Disordered Cosmos,* and it was reviewed brilliantly, won awards, sold decently, got me the opportunity to write this book, and also had a pretty huge conceptual hole in it. I called it *The Disordered Cosmos* and never said a word about the concept of order in relation to how physicists usually think about it. This problem actually didn't occur to me until we were near publication. I was so attached to the meaning the title had for me—it was the name of my first blog, inspired by an idea I'd had to explain dark energy using quantum gravity—that I hadn't considered what my training about the word "disorder" might suggest I should write about. I have long been afraid of the arrow of time, and not just because I inherited my father's tendency to go gray early.

Go to note reference *

[*] 110,000! is not a typo. The exclamation point means "factorial." Factorial is where a number is multiplied by every number smaller than it, down to one. So in this case it would be 110,000 times 109,999 times 109,998 times the next one down and so on. In other words, there are 110,000 numbers being multiplied by each other.

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III.

THROUGH THE LOOKING GLASS

“Curiouser and curiouser!” cried Alice (she was so much surprised, that for the moment she quite forgot how to speak good English); “now I’m opening out like the largest telescope that ever was! Good-bye, feet!”

—Lewis Carroll, *Alice’s Adventures in Wonderland*[1]

CHAPTER ELEVEN

THE PHOTON COLLECTORS

In which we see far beyond the stars

This is not a tall tale, as far as I know:

In the beginning, there was brightness all around. There was plasma and there were photons. The plasma, being a hot quantum soup full of charged particles, prevented the photons from getting very far without being consumed and repurposed. In the background, space-time expanded, stretching out the space that the plasma filled. The plasma cooled as it stretched, making it easier for local gravity to clump the particles together. The first hydrogen atoms formed, clearing the way for the photons to move about the universe without constantly colliding with something. Finally, the photons could fly free.

This true story means that all around you there are photons that have existed almost since the beginning of space-time. The most ancient cosmic artifacts have been and always will be our constant companions. We call these photons the cosmic microwave background radiation, or CMB. The CMB is all around us, and it was here before the sun, before the Earth. It will still be here after they're gone. The photons have been traveling across space-time since it was around 380,000 years old, their wavelengths stretching as space-time expands.

When they began, they looked like sunlight. But they have now lost a lot of energy and are low-energy microwaves—that is, long- wavelength light waves—that span the entire universe. Today, we scientists have the joy of watching the CMB with radio (microwave) telescopes. Because the photons that make up the CMB are everywhere and have been traveling across space-time since almost the beginning, they provide us with a powerful physical and conceptual map of cosmic history (while also adding to the noise in over-the-air TV signals).

The extent to which we understand the CMB is thanks to imaging and computing technologies made possible by the conceptual development of quantum mechanics. Only through understanding light as a particle and learning about how to synthesize quantum materials have we been able to develop quantum photonic technologies that allow us to do deep stargazing, have video calls with our best friends, and record the daily injustices across the globe that flood our social media (while our leaders, at best, do nothing and, at worst, are the perpetrators). The photon is a gateway to both the seen and the unseen. Photons also join with space-time to form the boundary of all we can ever know.[*] As I mentioned in chapter 3, in an expanding space-time there are indeed regions beyond the particle horizon that always have been and always will be beyond our reach. There are also regions of space-time that were within our cosmic event horizon in the past but are now outside of it, meaning we cannot receive communications from them. Photons draw the boundary around what it is possible to see. And the ways in which photons interact with both space-time and matter make them some of our most valuable informants about the universe.

Quantum Eyes on the Sky

Fall in the northern hemisphere is Andromeda season. That's when it is easiest to see our nearest major galactic neighbor—the only major galaxy that is visible with the naked eye, if you're lucky and have dark enough skies. Where I live, there's too much light pollution so it's not available to me without the help of equipment, but that doesn't stop me from looking up at where it is and reminding myself: There's a galaxy there. A beautiful, wondrous galaxy filled with over a trillion stars. Scottish astronomer Mary Somerville wrote in her incredibly popular nineteenth-century book *On the Connection of the Physical Sciences,* "The heavens afford the most sublime subject of study which can be derived from science."[1] Somerville's words reflect the attitude of generations of humans across our planet. We look up and see poetry. And science has continuously pushed against the boundaries of what we can see when we "look" at the heavens.

Today, most of what we know about modern cosmology is through a combination of theoretical work, observations, and instrumental innovation. Instrumentalists are the too often unsung heroes of astrophysics, talked of as if they are not real scientists but instead manual laborers. This reflects historical notions of what work is considered high-class and low-class. Manual labor has traditionally been associated with being poor and of lowly stature. Of course, this is a ridiculous social invention that serves lazy rich people. Think about how the nineteenth-century English gentry lived entirely off of other people's manual labor while they gallivanted around attending balls, jockeying for social status, and often making one another miserable. Jane Austen makes this visible in her novel *Mansfield Park*, where she highlights that the mistreatment of the novel's white woman heroine Fanny Price is part of a larger ecosystem that relies on the enslavement of Black people in the Caribbean. These types of hierarchies are pervasive, even among educated technicians like scientists. Astronomers have been unwilling to shake them, leading to a culture with theorists at the top and astrophysics instrumentalists at the bottom of a nonsensical intellectual hierarchy.

Instrumentalists play an enormously important role in astrophysics because it is only the work of instrument developers that allows us to capture and analyze quantum objects like photons. A telescope—like the NASA Cosmic Background Explorer (COBE) or European Space Agency Planck spacecraft, which both observed the CMB from space—is a complicated composite of technologies. First, optical elements—the instrument that will actually record the light collected by the optics. Second, the extensive computer programming involved in making that data usable. Only then is the data ready for any kind of analysis. The optical elements and recording materials that go into modern telescopes regularly rely on quantum understandings of both light and materials. All professional telescopes, whether they are on the ground or in space, use detectors that capture information about light by taking advantage of the quantum interaction between photons and the material the detector is made from.

Happily for non-instrumentalists (like me; maybe you too?) the technologies that start out in these telescopes often make their way into consumer products like our smartphones and the digital cameras that professional and hobby photographers around the world use—including for astrophotography. Usually when I'm staring up, looking for Andromeda and knowing I won't see it directly with my eyes, I'm standing next to one of my telescopes while it captures images of Andromeda. Astrophotography allows me to access a sky that hasn't been available to me as a (sub)urban dweller. In recent years, I've taken up amateur astrophotography, which has allowed me to appreciate the enormity of the instrumentalist's task and the brilliance with which my colleagues accomplish it. Have you ever used your phone to take a photo of the moon? You can! Want to go beyond using your phone? Luckily, barring the extreme challenges presented by increasing tariffs, which add to the consumer cost, we are living in a time when it's never been easier for an amateur to pick up astrophotography.

You might think that this was easy for me to pick up because I have two degrees in astronomy, but actually they were not especially useful for learning how to use equipment. I benefited from people who knew something about it writing up what they knew and passing it along, so I'd like to share with you the broad brushstrokes of how to pick out your own quantum eyes for the cosmos. First, you have to decide what telescope design you want to go with. Every single optical telescope assembly (OTA), the part that is primarily pieces of glass in a tube, has its pluses and minuses. I exclusively use refractors, which look a lot like what you expect a telescope to look like: The light enters a big magnifying glass, hits another piece of glass to focus it, and then goes to the observer's eye (or camera). Refractors are quite nice, although the cost seems to grow exponentially with size. If you want more magnifying power, the only way to get it is to make a bigger and longer telescope—the price and weight of the instrument grow very, very quickly. You can get more telescope for your buck by going with a reflector design, but this involves having a little mirror in the middle of the light-collection area, to bounce light back and forth as if the telescope length were folded inside the tube. Because of this mirror, reflectors sometimes need to be adjusted because their optics can get out of alignment. I'm too lazy for alignment and have chronic pain, so I've stuck with a lighter-weight refractor.

The basic type of OTA isn't the only consideration. The quality of the glass and how much of it there is will determine how good the images possibly can be. One common challenge is something called chromatic aberration. Part of the telescope's job is to focus light to a single point so that the image is sharp. But the focus point will be different for each wavelength of light. This will cause the colors of the image to be recorded incorrectly, and the quality (and thus cost) of a telescope will be determined in part by how well it handles this.

There are other decisions that an amateur astronomer must make when selecting a telescope. How will it sit on a stationary tripod and move with the night sky at the same time? Here we have to remember that none of us is ever stationary; we are on a planet that is both orbiting the sun and rotating around an axis. This means that the sky never appears stationary—as we look at any given object in it, the object's location in the sky is changing. The OTA is placed on a mount that is designed to move, either by the user manually moving it or through automated motion. I own the most automated one available, leaving the hardest part of the job to the people who designed the algorithms that ensure it moves correctly. The computer I use to run my telescope is so small that it sits on top of the OTA. Inside of that small computer there are millions of transistors that transmit electric signals, making the computer processing possible. Transistors are an invention made possible by a quantum-mechanical understanding of how electrons move in semiconductors, materials that can either conduct electricity or insulate against it, depending on how they are tuned. Home astrophotography is made possible by the advent of quantum mechanics.

Of course, my computer can't record what the telescope is seeing—not by itself anyway. For almost two centuries, professional astronomers have used a camera of some kind to capture images of the objects they are studying. Imaging technology development for astronomy has often helped drive technological developments that then widely benefit everyone, like getting a camera sensor that is small enough to fit into the latest smartphone. The technologies in use are all quantum technologies—by which I mean that they are made from materials whose quantum nature allows us to collect photons in digital devices, quite distinct from the way analog film works. Film works through a chemical process, while today's digital cameras are circuit-based. The most popular brand of consumer telescope cameras, ZWO, use CMOS sensors, which are sensitive to the impact of each photon, literally to the point of effectively counting photons. Professional telescopes sometimes use CMOS sensors, but there are other options. In Chile, the Vera C. Rubin Observatory camera, which at 3.2

gigapixels in size is the largest camera in the world, uses CCD sensors, just like the iPhone front-facing camera but almost three hundred times bigger, so big that someone who is five feet and four inches or shorter could fit inside. Consumer telescopes, like professional ones, are quantum eyes on the sky.

A digital camera can be placed on the viewing end of an OTA and used to capture digital photos, like the one I took in Figure 11.1 of the Ring Nebula (to find this figure, look at the photo insert). We can also use camera lenses like OTAs, just as I did in Figure 11.2, when I took a series of timed images of the Milky Way over Joshua Tree National Park with a mirrorless digital camera and then quite amateurishly compiled and cleaned up the data using the Affinity Photo 2 software (you'll find this figure in the photo insert and it's important for me to emphasize that I'm not especially skilled at this, but I continue to work at it).

Understanding the quantum nature of photons and materials alike is key to our ability to see the outer cosmos in extraordinary detail. Developing the skills to use these technologies used to require significant investment. The good news is that these days, you do not need to be an expert to try your own hand at it. There are one-piece telescope sets that include an OTA, mount, and camera all packaged together and priced as low as $350. These are easy for anyone with a smartphone to use.[*] I'm excited about these devices because they are especially useful to people in light-polluted environments. Rather than showing you the sky the way it looks to the naked eye, they take a series of images with exposures for periods of ten seconds or more and then add them together. By adding the brightness of the collected photons together, they can make a stronger image. Objects that are totally invisible to human eyes then become beautiful, brilliant objects on our cellphone screens. I had this experience the first time I saw Andromeda. I have a small portable smart telescope, which I took with me on the trip to Joshua Tree. I was too busy with work to plan my observations, but was thrilled when I looked up, star atlas phone app in hand, and realized I could see our neighboring galaxy. But it was just fuzz, until I gave my telescope ten seconds with it. Within minutes, I could very clearly see the dust lanes (Figure 11.3 in the photo insert) and two of Andromeda's brightest satellite galaxies, which are gravitationally bound to it (look at the top left and bottom right).

In my own backyard, I've learned that one of the wonderful things about doing astrophotography is the way you start to feel the rhythms of the universe. You get to know the moon's cycle and travel with it through the monthly sky. You develop an instinctual understanding of when it will be bright, when it will be in an annoying location for taking images, and when it will leave you alone. Your year starts to be organized around what will be in the sky, the way it was for our ancestors. This is all true of visual astronomy too, of course. But with astrophotography, you get to watch the sky appear, one ten- to sixty-second snapshot at a time, knowing every photon captured is a quantum messenger from the cosmos beyond our atmosphere.

The hard work of astronomers decades ago has made it possible for us to look at the cosmos from our balconies and fields, streets and backyards, and share what we see on social media. But our increased access is counterbalanced by growing light pollution. Airea D. Mat-thews proposes in her poem "Select Passages from *The Holy Writ of Us*" that "light is a gentrifier": "Chaos 30:7: Darkness was here first. Light is a gentrifier. Darkness is not called un-light. Light is un-dark."[2] She's correct in a quite literal sense: Light pollution has brightened our night sky and made it wildly inaccessible to many, especially poor and working-class communities. Poorly planned urban lighting has indeed gentrified our skies, making it more difficult for us to discern the difference between photons arriving from our nearest major galactic neighbor Andromeda and the all-wavelength white LED light that the city installed on our block.

Given the right visibility conditions, Andromeda is clearly visible to the naked eye. It is a large galaxy and, in cosmic terms, close by, so it is relatively bright. But most of us will never see it this way. The reason Andromeda was a difficult-to-find blur the first time I saw it is the light pollution and smog from nearby urbanizing environments. We should be concerned about light pollution because of the way it disrupts our ability to witness the cosmos unaided. Even in cities where there is already so little to see, the situation is getting worse. My astrophotography mentor, Marvin, told me that in the five years since 2020, his ability to see any celestial objects from his backyard in Los Angeles has made his hobby almost impossible. The tragedy here is not just the way we lose out on an important ancestral and cultural experience or the impact on animals that rely on darkness. Light pollution steals the stars from us—and that means losing the past too.

Interpreting Cosmic Messengers

The constant arrival of cosmic photons means we receive messages from the past all the time. Photons are our most trusted messengers. By the time we see or experience a photon, whatever information it delivers about its origins is potentially out of date. The finite speed of light means that photons never deliver information to us instantaneously. The sun is eight light-minutes away. The light that falls on your skin is eight minutes old. When I use my little telescope with a solar filter to observe the sun during the day, in that now, I'm seeing the sun as it was eight minutes earlier.

The photons that left the sun eight minutes ago aren't necessarily the ones that interact with the quantum photon detector in my telescope's camera, because first they traveled through the atmosphere and may have been absorbed and re-emitted by atmospheric elements. Does that difference matter? Not particularly. All particles of a specific type are alike. A 5 megaelectron-volt photon (high- energy gamma-ray light) and a 500-nanometer photon (low-energy visible wavelength) are distinguished only by how much energy they contain.[*] Switch the roles of the two particles (high-energy to low- energy or vice versa), and no one would ever know. Nevertheless, the energies of the photons that arrive tell us about our multifaceted sun—an ever-changing nuclear-fusing plasma fireball. A photon created in its core can take up to a million years to reach its surface, meaning that it takes that photon about 1 million years plus 8 minutes to arrive to us.

The interaction of light with the expansion of space-time shifts what it means to think about distance. The ruler that governs distance across space-time is expanding; this is what the shorthand "space-time is expanding" means. As it expands, photons experience a phenomenon known as redshifting. Remember in chapter 4 when the little squiggly lines on top of the balloon were stretching with the expansion of space-time? (See Figure 4.1.) Redshifting is the name for that stretching. The stretching of space-time and light along with it means the wavelength of the light gets longer—which means it also gets redder. Ever notice how ambulance sirens change pitch both as they get closer to you and then as they go away from you? The change in pitch is also a change in wavelength, the sound bunching up and growing shorter as it gets closer; stretching out longer as it moves away. Light experiences this same squeezing and stretching of its wavelength as the source moves toward or away from a detector, as shown in Figure 11.4.

At the start of this chapter I said that CMB photons started out like sunlight. Like the sun, they roughly radiate like a blackbody (see chapter 7 for a refresher on blackbodies). But CMB photons have been stretched out with space-time's expansion. So initially their blackbody curve peaked at a short wavelength, which corresponds to higher frequency, higher energy, and thus higher temperature. Today, the photons have been stretched out and are long microwaves with an associated blackbody temperature of T=2.73 Kelvin (this is equivalent to −454.76° Fahrenheit or −270.42° Celsius)—so cold that we can't detect their presence without a microwave telescope (remember, microwaves are light with long wavelengths).

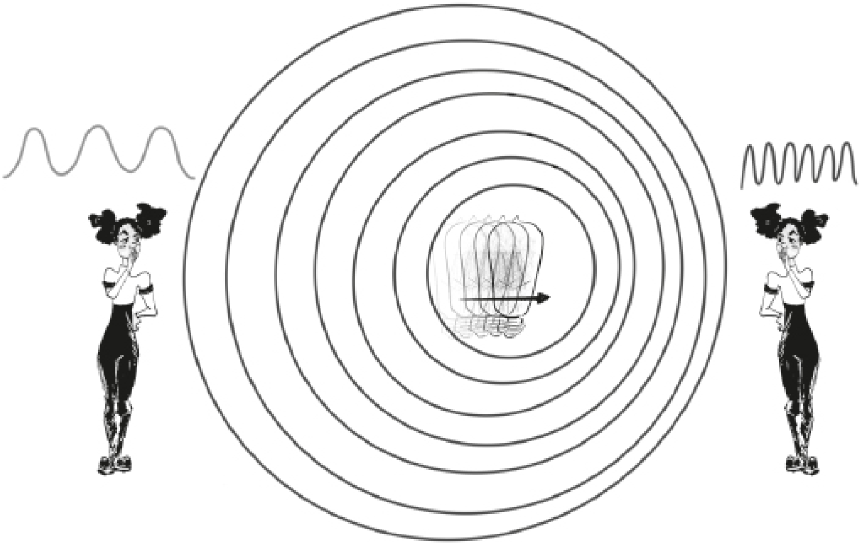

Figure 11.4. In this figure the source—the light bulb—is moving to the right. The waves scrunch together in the direction it is moving in, while they pull apart behind it. Those scrunched-up waves are shorter wavelengths. This corresponds to a higher frequency—in the same amount of distance there are more peaks. The reverse is true behind the source. The wavelength is longer and the frequency is lower.

Thanks to what we know about how photon energies change as they journey through space-time, we can translate redshift into information about distance, and this is true for observations of all kinds of objects, not just the CMB. This knowledge is predicated on a quantum understanding of the interaction between light and matter—the same interaction that explains why higher melanin content in skin increases that skin's resilience against sunlight's capacity to burn.[*]

Remember that an atom can absorb and emit photons only at specific energy levels, which correspond to discrete frequencies? This was a key factor in the photoelectric effect, described in chapter 7. This is related to the quantum structure of the atom, roughly corresponding to Bohr's model. Now consider two giant cosmic clouds of atoms, which we will name for everyone's favorite pair of guncles, *Sesame Street*'s Bert and Ernie.[*] We shine blackbody starlight on them. Bert is in a lower-energy state, and some of the blackbody light resonates with his atomic composition and energetic state. The way photon interactions with atoms work, he will absorb the photons and become more energetic. Meanwhile, Ernie is already quite high- energy and doesn't need any additions. In that high-energy state, he may spontaneously go to a lower-energy state, emitting photons in the process. What would we see then? In Bert's case, we'd see a black-body spectrum (see Figure 7.1) that has a dip around the wavelength (or frequency, if you prefer) of the photons that he absorbed. Bert has literally taken the photons out of the spectrum. In Ernie's case, we would see emission only at the wavelength of photons that he has radiated.

Wavelength is an abstract term that in the visible range of light corresponds to something quite familiar: color. We can see this in twentieth-century city lighting, which made use of sodium gas: The orange of old streetlights corresponds to a characteristic energy transition wavelength for sodium. More generally, we can think of the colors associated with these energetic transitions as creating a spectrum. You may have first encountered the concept of a spectrum through the idea of a rainbow as decomposed visible light. When we speak of spectrums in general terms, we are often referring to these characterizations of photon emission or absorption, as in the case of Bert and Ernie. So, maybe Bert (who is yellow) is missing orange because his atoms ate it. Maybe Ernie (who is orange) is only emitting that color because that is his nature.

Helpfully, using labs on Earth, at least one of which was closed by the Trump administration while I was drafting this book, we can characterize what emission spectra look like for different atomic elements. We know their shape and the relative location of the emission and absorption lines. This means that when we look up to the sky, we can learn about the composition of objects we are examining by looking at their spectrum. Of course, expansion complicates things: The emission and absorption lines are no longer where we expect them to be, because they are redshifted. This is why their shape and relative location are also important—we can calculate how much they shifted. And knowing how much they have shifted can be translated, using general relativity, into a distance measurement—thus, we also learn how far away they are from us. This is one of the most important techniques for measuring cosmic distances.

Bend It Like *Us*

Because their journeys reflect the structure of the metric, photons are the particle that we have historically used to map out our universe on the largest scales. We see the CMB from the earliest moments, which provides an image of space-time at about 380,000 years after the Big Bang singularity. But looking at the stretching of light by space-time expansion isn't the only way photons give us information about the past and present nature of our cosmos. We can also look at images of distant galaxies and receive information about those galaxies—and the shape of the space-time terrain that light has traveled through to reach our instruments.

Think about a plane flying from New York to Accra, Ghana: It doesn't travel in a straight line, because the surface of the Earth is curved and the plane's trajectory must follow that curvature. We cannot see or even correctly visualize the curvature of space-time, because it is four-dimensional. But we can see the effects of this curvature.

The idea that space-time is curved and expanding means that the paths light follows are not always straight—think back to Figure 3.2 and the discussion in chapter 3. Photons travel the straightest possible line available to them. We know that the curvature is locally determined by the presence of massive objects. So, imagine a scenario in which we are on or near Earth (not a stretch, right?) and there is a galaxy far, far away that we want to observe. Between us and the galaxy there is a massive galaxy cluster, which could have hundreds or even thousands of galaxies that are gravitationally bound to one another. The mass of the galaxy cluster will cause the spacetime in the foreground—between us and the distant galaxy cluster—to curve, forcing light to travel on curved trajectories, as you can see in Figure 11.5.

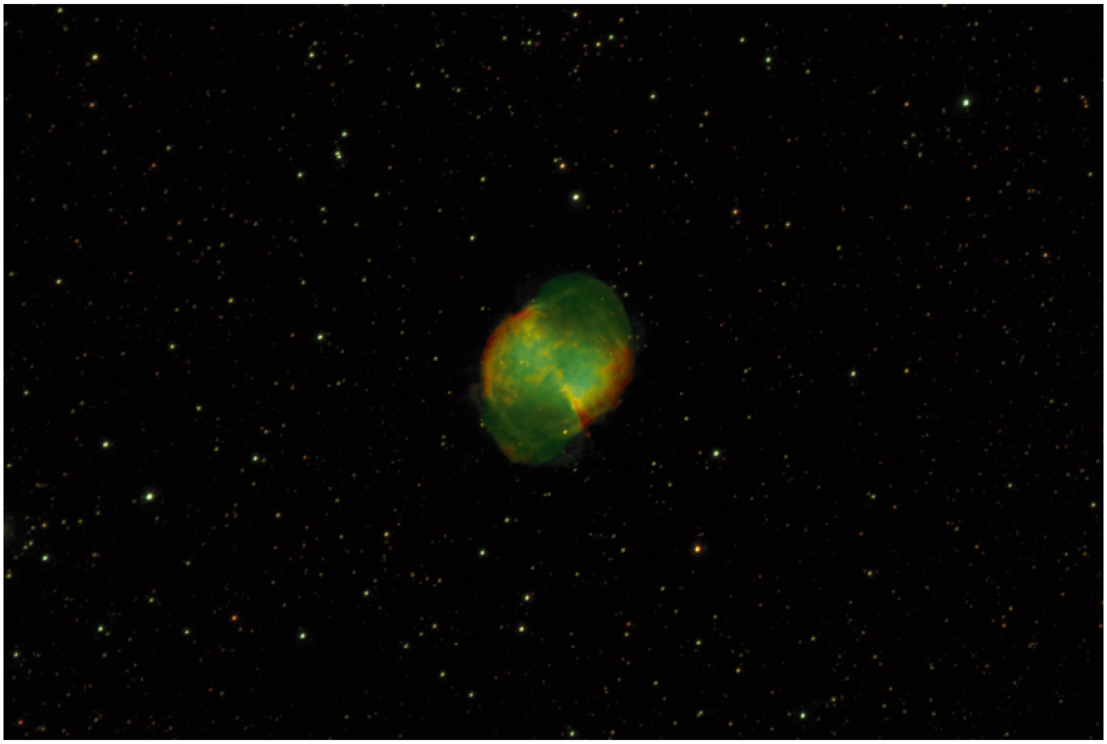

Figure 11.1. The Ring Nebula, June 2024. This is the remnant of a dead star, which has a compact object known as a white dwarf in its core. This image is a composition of about two hours of data collected in my New Hampshire backyard using a 102-millimeter aperture OTA and a 26-megapixel astrophotography camera. I did some very light touching up to darken the sky and brighten the nebula's features. I did not do any of the additional steps that one might take, including using calibrating images that would reveal more data by removing errors in the camera's sensor. In other words, this beauty is the kind of image you can get without having to put in a lot of effort or technical know-how!

Figure 11.2. The Milky Way, June 2024. This is how our galaxy looks to us from the arm where our solar system sits. This image is a composition of about ten minutes of exposures taken near the Cholla Garden in Joshua Tree National Park using a 33-megapixel mirrorless camera and 24-millimeter lens attached. As a learning exercise, I adjusted the digital data to draw out the right features in the image, which won second place in the 2024 Black Space Week Contest organized by Black in Astro.

Figure 11.3. Andromeda and two of its satellites, June 2024. This is our nearest major neighbor galaxy, and in fact the Milky Way is on a collision course with it. Andromeda is so close to us that it is too big to fit into the frame of my Seestar S50 telescope, which is why the image cuts off the edge of the galaxy. I took the image before software updates made it easy to take

multiple images and add them together to make a more complete one. This is about two hours of data compiled together. The image is not retouched or calibrated.

Figure 11.6. A magnificent example of gravitational lensing, featuring an Einstein ring that seems to encircle the central object. Einstein rings occur when there is alignment between the source, lens, and observer. (See Figure 11.5 for a helpful diagram.) From the European Space Agency website: "The narrow galaxy elegantly curving around its spherical companion in this image is a fantastic example of a truly strange and very rare phenomenon. This image, taken with the NASA/ESA Hubble Space Telescope, depicts GAL-CLUS-022058s . . . The object has been nicknamed by the Principal Investigator and his team who are studying this Einstein ring as the 'Molten Ring,' which alludes to its appearance and host constellation."

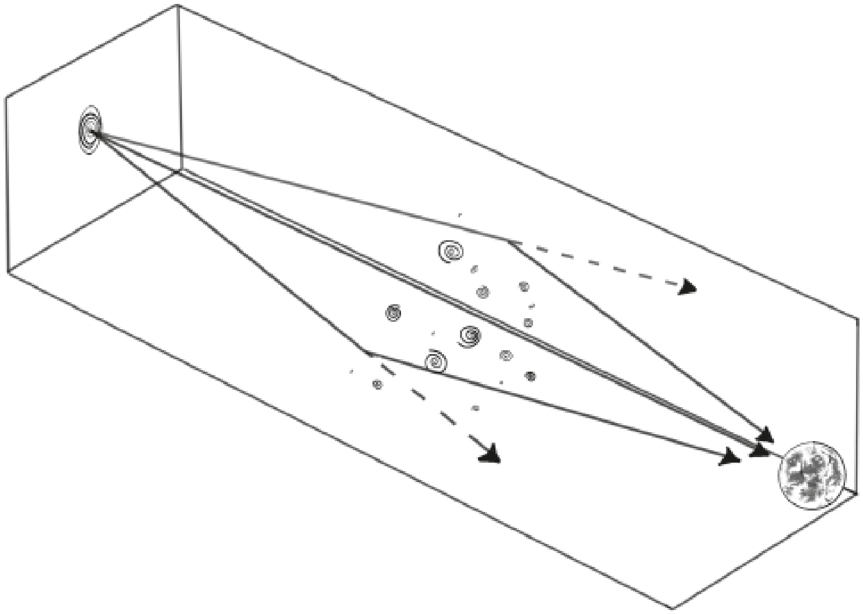

Figure 11.5. How gravitational lensing works. Between the Earth (the observer) and the galaxy (the source) we wish to observe, there is a galaxy cluster (the lens), curving space-time, leading to light (the lines) traveling on curved trajectories.

The visible outcome can be **dramatic,** so **dramatic** that I have put the word **dramatic** in bold (three times now). To understand how this is possible, think about a scene from Jordan Peele's horror film *Us,* which features the boardwalk in Santa Cruz, California. In Peele's Santa Cruz, there is a funhouse mirror maze where one of the characters gets lost—and possibly switched with a doppelgänger. If you've seen the film, you might remember that all throughout this scene, the funhouse mirrors distort the characters' view—sometimes they see themselves stretched out; sometimes they see more than one of themselves. Space-time can do this too. I don't mean that in some metaphorical sense—I mean that space-time also creates optical illusions by transforming how light arrives at the viewer. This phenomenon is called gravitational lensing.

Think of space-time like fine hairs—getting its edges laid, with the most elaborate swoops the universe has to offer. That's gravitational lensing. There are multiple effects involved. The most visibly spectacular (see Figure 11.6 in the photo insert) is that multiple copies of the same galaxy can appear in our image. It's easy to tell the difference between this effect, which is known as strong gravitational lensing, and a broken telescope: With the former, often these replications are accompanied by characteristic distortions that simply don't happen in a telescope. We might see an increase in brightness or what we can call "bananafication," where the galaxies seem to arc like a waxing crescent moon or a cookie after Cookie Monster has taken a giant bite out of it.

Sometimes, though, gravitational lensing isn't obvious to the human eye. In the case of weak gravitational lensing, there are distortions to galaxies but no apparent copies of them. To detect weak gravitational lensing, we use finely tuned computer algorithms to look for patterns in the shapes of all the galaxies that appear in an image. If there are correlations—for example, if they all show the same level of bananafication—then we know that the shapes we are seeing aren't the natural shapes of the galaxy but are instead distortions due to gravitational lensing.

Lensing can happen to any cosmic light, including the cosmic microwave background radiation. As the CMB photons travel through space-time, they will cross paths with the plethora of gravitational wells that exist due to the presence of galaxies and galaxy clusters. Their pathways will experience observable deflections due to these gravitational interactions. Gravitational lensing presents us with a new boundary: the place where we can no longer directly see an object as it is, instead only reading it through the way that space- time transforms its visible emissions.

To put things in perspective, let's remember what galaxies are: complex structures, which all have their beginnings in the CMB. I mentioned earlier that the CMB has a temperature associated with it. There are actually small variations in the observed temperature. Each variation is only 0.00001 degrees (Kelvin) more or less than the average temperature. But these fluctuations in temperature, while extremely small, are also mighty. We are fairly confident that they are a reflection of quantum fluctuations in the vacuum of space-time during inflation. These variations correspond to regions where there was a little more matter-energy and a little less matter-energy: Where there was a little more, still more matter was attracted, due to local gravitational effects. In other words, these fluctuations correspond to the beginnings of structure formation in the universe. The beginning of *us*. And it is the end point of these fluctuations—galaxies and galaxy clusters—that lensing will observably affect.

In the case of galaxy observations, we don't need to worry much about gravitational redshift. But gravitational lensing is a very noticeable spectacle.

Whether we are dealing with strong or weak gravitational lensing, we can reverse-engineer a determination of how much matter there is between us and the background image using a combination of sophisticated algorithmic analysis and results from general relativity. And these observations, in turn, lead us to a shocking insight: The way the light is distorted isn't what we would expect. Observation indicates the space-time is more bent than it should be if the only matter present is the type that gives off light. As in, there appears to be matter that's not emitting light—and it's bending space-time. I don't mean that some of the matter is radiating in a bandwidth our telescope isn't detecting and that we need a new instrument. Instead, it appears there is other matter—matter that neither radiates photons of any kind in noticeable amounts, nor absorbs them.

This apparently invisible matter, called dark matter by scientists, does not seem to be a photon collector. It has no apparent sense of color because it has no evident relationship with light. Now, of course, it may be that it radiates a little—but so far, we've never seen any evidence (at least, not that the research community agrees on) that a photon came to us directly through interaction with dark matter. It may be, therefore, something of a misnomer to refer to this matter as "dark"; "transparent matter" or "invisible matter" might be a better name.[*] Recent Nobel laureate P.J.E. Peebles calls it "subluminous matter."[3]

We'll return to dark matter as a particle-physics problem later, but for now I want you to notice that the absence of light can be just as informative as its presence. Light has also been critically important as a source of scientific inspiration. Our attempts to understand light's energetic properties play a unique role in the history of quantum physics. We know that CMB microwaves are disturbances to the electromagnetic field *and* also particles called photons. Before 1900, light was thought of as a wave, a fluctuating, classical electromagnetic field. But then light had to be understood as a wave and a particle—the photon—simultaneously. As Steve Weinberg points out in his classic book *The Quantum Theory of Fields,* "The photon is the only particle that was known as a field before it was detected as a particle."[4] Ultimately, the photon lit the pathway to relativistic quantum mechanics, which we will come to in the next chapter. Photons illuminated the queer, metaphor-transgressing world of quantum field theory for physicists and had me running around shouting, *Photons, photons, photons! It's a field of photons!* You're about to see why.

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* *All You Can Ever Know* is the name of a beautiful memoir by Nicole Chung.

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* As of time of writing, the cheapest of these is the Dwarf 3. I personally own a Seestar S50, which costs between $450 and $549, and would highly recommend it (and am not getting paid to do so). While I was drafting this book, the Seestar S30 came out and people seem pretty pleased with it as a somewhat cheaper alternative at $400. Unfortunately, thanks to tariffs, prices on all of this equipment keep going up. All of these instruments are great at solar imaging in the daytime, and if the U.S. were serious about K–12 science education, every school in the country would have one.

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* Sometimes we refer to them by their energies and sometimes by their wavelengths or frequencies—this is cultural. We can convert between them.

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* To learn more about this, check out "The Physics of Melanin" in my first book, *The Disordered Cosmos*.

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* That's slang for "gay uncles."

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* See chapter 6, "Black People Are Luminous Matter," of my book *The Disordered Cosmos* for a discussion about how the word choice impacts the social life of "dark matter."

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CHAPTER TWELVE

YOU ARE AN ABSTRACT CONTRAPTION MADE OF NOTHING

In which you are kind of like an electromagnetic field but also very different from one

As a child, I used to think all the time about what image was beyond the reflections that I could see in a mirror. I would get very close to it and try to look around. I'm not sure where I got the idea to do this, although increasingly I think it's Lewis Carroll's fault. At the start of his sequel to *Alice's Adventures in Wonderland, Through the Looking-Glass,* Alice is similarly curious. Talking to her cat, Kitty, she explains how she maximizes how much of the Looking-glass House she can see in the mirror and how it looks so much like her own house, "only you know it may be quite different on beyond. Oh, Kitty! how nice it would be if we could only get through into Looking-glass House!"[1] Alice then tries to walk into the mirror. When I tried this, my face hit the glass. Alice has a different experience, walking through the looking glass and finding herself in a world that looks a lot like the one she just left, but with some key differences.

The same thing happens to the quantum theory of photons when we put it in conversation with relativity. Remember, electromagnetism is already relativistic by definition, so this is in some sense merely a matter of self-consistency. Electromagnetism is described by a field and photons by a wave equation. If we imagine how to merge these two pictures, it seems almost natural to consider the possibility that if there is any sort of quantum electromagnetism, it must take the form of a *quantum* field. So, light was our first field theory, which turned out to be relativistic by definition. And photons were our first quantum theory. It perhaps should not be surprising, then, that a properly relativistic theory of photons is our first quantum field theory. But they will not be our last. Much like Alice, we are now finding that every time we think we've met the most curious thing, everything gets "Curiouser and curiouser!" Down, down, down we go, into empty space, from which we will emerge with the quantum nature of strawberries.

Horror Vacui

Imagine empty space. Maybe, like me, you think of the scene toward the end of the film *The NeverEnding Story* where the Nothing has destroyed nearly everything, and Bastian and the Childlike Empress are ready to restart the universe from a single grain of sand. Everywhere around them is a sense of nothingness—except for these two children, one real and one imaginary, who refuse to let go of dreams. As a child watching the movie—and later an adult reading the Michael Ende book from which the film is adapted—I understood that I had to suspend belief to imagine a universe that is totally empty (except for the founding pair).

But it turns out that this conception is not so far from how things work in reality. In the real world, there is no such thing as empty space, the so-called vacuum with nothing in it. Even where there is apparently nothing, quantum mechanics says there is always something. We find our first hint of this when we try to solve the quantum wave equation (widely known as Schrödinger's equation) for the energy in a very simple system: a spring bouncing back and forth. You might think the lowest-energy state of a spring is no energy at all, and classically, that's true. But when we do the quantum calculation, there is something called zero-point or vacuum energy that is always present. The system never drops to no energy at all. Quantum calculations suggest that this is generally true, that there is *always* energy in space-time; there is *no* such thing as empty space-time.

If we put this new lesson about vacuum energy in conversation with the uncertainty principle, a delightful phenomenon emerges: The vacuum not only has energy, but the energy fluctuates. This is because one of the features of quantum mechanics, related to Heisenberg's uncertainty principle, is that the more exact and smaller our measurement of time, the less exact and bigger our measurement of energy, and vice versa. We can either know the time precisely or the energy precisely, but not both. This means that, over a short enough timescale, additional energy on top of the vacuum energy flickers in and out. Even if we could somehow remove the vacuum energy, the flickering would still be there.

As Neo says in *The Matrix,* whoa. Looking at the universe from its quantum margins allows us to see space-time—and all the philosophical questions associated with it—in new ways. "What is the nature of empty space?" seems like an easy question, if we take for granted that space exists independently of its contents. And in the Newtonian world, that's how it actually works. If you read Isaac Newton's *Principia,* you'll find that he doesn't appear to have worried about questions regarding the fundamental nature of space at all; he took it as a given: "Absolute space, of its own nature, without relation to anything external, always remains homogeneous and immovable."[2] In other words, rather than reasoning himself to a conclusion about what space is, with an explanation of its properties, Newton simply declared it. He identified the nature of space as something he had to address, but not as a central point in his text.

Most physicists are never encouraged to pick up the *Principia*. I didn't until I was working on this book. I was amused to find that this question that had given me so much trouble was a matter of a paragraph-long dispensation to Newton. Newton never considered the possibility that there might be more to the nature of space than . . . just sitting there doing nothing.

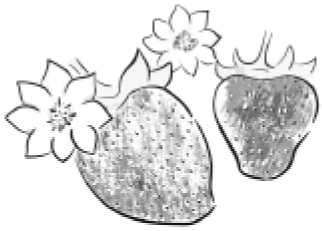
By contrast, quantum physics insists that empty space is not empty. And neither theory of relativity takes a position on this question at all: Space-time can be empty, it can have stuff in it, whatever. General relativity really doesn't care. In this sense, quantum field theory is our most fundamental theory that genuinely deals with matter. Thus, we should only be looking to quantum physics for information about matter and energy, whether it's what's in empty space-time (an oxymoron, I know) or whether it's in a space-time that seems to be matter-ful. There is an invitation lurking here: to think conceptually about what it would mean to have a relativistic quantum theory of the vacuum and also to understand empty space as directly related to the existence of matter.

Happily, we already know of one theory that is both relativistic and quantum. The photon is, functionally, quantum electromagnetism. It obeys special relativity, and we have some understanding of what its quantum features are. Classically, it is already a field. We have to be a little careful here because it's easy to conclude that the electromagnetic wave and the quantum wave function are the same thing. They aren't. An electromagnetic wave is an observable wave—light—caused by a disturbance to an electromagnetic field. The quantum wave function contains information about the state of a particle and gives probabilistic information about its dynamical properties—like location, speed, energy, and so on. It is not directly observable. But the fact that the electromagnetic wave emerges from a field suggests to us that a full quantum theory of light should actually be a field theory, not a wave theory. The conceptual leap required is this: Just as a classical field has a value at every point, maybe a quantum field has something like a wave function at every point. Maybe this is true for all particles, not just photons.

What emerges from just thinking about the intersection of special relativity and quantum mechanics is everything we can see. I'm not exaggerating! Sephardi Jewish philosopher Baruch Spinoza articulated the fear of empty space—horror vacui—in particularly memorable terms: "Nature abhors a vacuum."[3] And it turns out that a true vacuum doesn't exist. There's always something—always a quantum field.

Strawberry Fields

Behold the strawberry plant:



OK, not really. It's only a model. And it's evidently missing a few parts. Does it really get to the heart of the strawberry? While S. Zainab Williams did a delightful rendering, it doesn't have any quantum fields in it. And what is a strawberry, really, if not quantum fields? And by that I mean: What is the differential equation for a strawberry? As the physicist version of John Lennon might have put it when recalling his childhood in Liverpool, *Let me take you down, because I'm going to . . . quantum strawberry fields.*

Strawberries are wild plants, but for the most part the ones we consume are grown in fields as part of large, corporate farming operations. In my home state of California, strawberries are cultivated by often underpaid immigrants who face long hours, backbreaking labor, and some of the most challenging working conditions in the United States.[*] We can understand the challenges of their working conditions through the lens of thermodynamics—the heat alone is incredibly challenging—and the mechanics of continuously being bent over picking and carefully moving boxes of tender fruit.

These working conditions are in turn shaped by a combination of social and political choices intersecting with a market driven by the strawberry's popularity. This popularity makes sense because strawberries are the most delicious fruit to ever evolve on this planet and be cultivated by humans. The ones we are most likely to eat are all intellectual descendants of French cross-breeding between strawberries from the region now known as Virginia in the USA and ones found in the region now known as the country of Chile. In Palestine, they are on the list of foods whose import is heavily restricted by Zionist occupiers.[†]

It's strange to think of the way a flower can become a symbol of colonialism while remaining a powerful expression of the delicious physical logics of the universe.[‡] And a flower is all that a strawberry is, essentially. The strawberry is simply the flower's final form. In the strawberry—which, botanically speaking, is not a real berry—the delicious fleshy pulp comes from the receptacle of the flower, which contains many ovaries. Those ovaries eventually become what we call seeds on the exterior of the fruit: an aggregate. Technically, the things we call the seeds are the fruit, and they have seeds inside of them. The delicious part is just the holding place for the fruit. It's a smart way to get animals to eat you: delicious flesh; small, digestible seeds to spread around via poop.

The strawberry's incredible flavors come from a variety of chemicals that are largely composed of just a few atomic elements: hydrogen, carbon, and oxygen. Those atomic elements are made of electrons, protons, and neutrons.

You may recall that the electron is an elementary particle, while protons and neutrons are both composites made of elementary particles known as quarks. Now, having read as much as you have about quantum mechanics, you might find yourself thinking, *These should all be represented by wave functions, then*. And right you are, if we want to stay in the realm where relativity is irrelevant.

But we also know that on the scale of atomic composition, the concept of relativistic matter-energy equivalence—that mass and energy are interchangeable—becomes important. This is particularly noticeable at what are called "relativistic scales." You might think that atoms are so small that relativity cannot possibly come into play, but let's consider the forces at work that we know about. Hydrogen is comprised at least of a proton and maybe an electron, if the atom hasn't lost it. The electric force will be relevant because electrons and protons will attract each other. Carbon is the sixth element in the periodic table, so it has six protons in its nucleus and up to six electrons in its orbit. Those particles will attract each other, while the spins of the electrons will have a corresponding magnetic field (exactly like what happens in the Stern–Gerlach experiment). The forces involved here are actually quite strong for their scale, which means the electrons have energies where relativistic effects necessarily come into play. That suggests that relativity should be one of our considerations. In other words, non-relativistic quantum mechanics is insufficient if we care to explain a strawberry.

Which is to say: to understand the strawberry, we have to think about empty space. We need relativistic quantum theories—quantum field theories—for particles besides the photon. In basic quantum physics, the fundamental wave nature is an abstract piece of information that can be used to give probabilities for observables. With quantum field theory, there is something of a shift. Think back to the sugarcane fields my mom knew so well as a child and imagine wind blowing through those tall, sweet blades of grass. This is a wave passing through a field—or as we physicists might say, propagating through the field. Without the wind, the field is in its vacuum state, with the tips of the sugarcane grass blades at various random heights. Metaphorically speaking, the presence of the wind disturbs the field's vacuum state. And the place where the wave disturbs the field is akin to what we call an excitation of a quantum field: This is a moment of creation, where a particle comes into existence.

In other words, particles *are* disruptions to the quantum field's vacuum state—excitations of the quantum vacuum. There is a limit to this metaphor, because with real quantum fields, particles can be created—but they can also be destroyed. At least, that's one interpretation. (We'll return to this later.) But the gist is: The particles that make up strawberries are something that came from absolutely nothing.

It's also important to remember why we used the "field" concept in the first place: We wanted to find something that can obey relativity and be quantum-mechanical at the same time. I defined a "field" back in chapter 6 as a process that takes a location in space-time as input and outputs the strength of something at that location. In this case, the field itself represents the possibility of a particle—like the photon or the electron. What it outputs is the probability of one or more of those particles existing as an energetic representation of the field—an excitation—at a specific point in space-time. The size of the wave determines the number of particles at any given point: the bigger the wave, the more particles manifest.

These quantum fields exist everywhere in space-time. That means that all electrons come from the same field, which also means that they are all interchangeable. There is no such thing as a unique electron that can be distinguished from other electrons. An electron could be replaced with another one, and the universe would be none the wiser for it. Importantly, there are not excitations everywhere—there is not something behaving like an electron in every single location in space-time. The places where there are excitations correspond to phenomena that we witness as particle-like and which can come together to form atoms, molecules, strawberry plants, and eventually strawberries. And so strawberries are, at base, composites of excitations of quantum fields interacting with each other. Strawberries look and feel classical. But deep down, they're quantum.

Quantum field theory isn't just an interesting idea because it happens to merge special relativity and quantum mechanics together. Quantum field theory gives us new insights. It provides a vocabulary for interpreting phenomena like flickering energy in the vacuum—for understanding what those energy fluctuations are. The vacuum-energy fluctuations are particles flickering in and out of existence. Remember from the previous chapter that we are pretty sure that these fluctuations explain some features in the cosmic microwave background radiation. Those fluctuations are also the beginning of structure formation—the beginning of the field I enjoyed picking strawberries in as a child. So now we know: The quantum fields that make up a strawberry are everywhere, and fields like them are the basis for everything we've ever seen. These strawberry fields are more likely to express as a strawberry in certain locations. But given how many different things need to happen at the quantum physical level for a strawberry to happen, we can ask: *Why* is there a strawberry?

Statistically speaking, it's because the quark and electron fields have made a lot of the particles needed to create the atomic foundation for a strawberry, hydrogen. In just a couple of chapters, we'll return to how you get the rest. But it all begins with the vacuum, in the apparent emptiness of a space-time that is actually teeming with quantum fields. That's where everything, including us, comes from. You're an abstract contraption made from nothing.

The End of the Point

Fields are a very different view from the particle picture, conceptually. In the Newtonian picture, you'll recall, particles are thought of as little points, the smallest point that you can imagine. The punctuation of a period (.) is enormous compared to the size we are thinking about. Quantum mechanics forces us to rethink this picture, at least sort of. Now a particle is both a point and a wave at the same time. It behaves like a wave, but also the wave that represents it doesn't exist in the physical space where we seem to live our lives. We don't entirely understand that, but we live with it. Enter quantum field theory and the standard model: Now, particles are not points or waves but rather energetic manifestations of fields that *exist* everywhere but don't *visibly manifest* everywhere. It's almost like what Slick Rick says on the track "Mother Teresa" applies: "*We are now qualified to do anything with nothing.*"

If you think back to your understanding of electromagnetism, perhaps you can develop some intuition for this. The electric and magnetic fields exist everywhere, but all that existence does is provide us information about what might happen in every location given the right physical interactions. Quantum field theory is a kind of extension of this idea, although it is not quite synonymous with it. In the classical electromagnetic picture, the electric field and the magnetic field simply exist in every location, and they work by acting on charged particles. The picture for quantum field theory is far more general. The quantum field exists everywhere, and it works by acting on the vacuum—b ut it has to be prompted to act on the vacuum.

All sorts of philosophical questions come up here, and they are pushed to the side even more than the interpretive problems in quantum mechanics. A typical quantum field theory textbook doesn't even admit to the possibility of interpretation challenges. It's deeply annoying for me as a writer, actually; there's very little guidance on how I might interpret the meaning of quantum field theory for a general audience, other than to say what I've said: "Particles aren't really points anymore. It's weird. Trust me." But I want you to do more than trust me; I want you to get a sense of what I see when I look at the world and ask the question "What is a particle, anyway?"

Thankfully, philosophers are not ones to let niche, abstract questions go unasked, and there is a useful literature about these questions that is mostly untouched by physicists. The question of what a particle "is" can be recast in terms of what we need a particle to do to get the world we live in, which is still a question of basic mechanics: We need a particle to go from one place to another. We still want to be able to characterize the motion of matter. What's changed is our sense of what counts as matter (now light is included!), what categories matter comes in (mostly dark matter and dark energy, with a little standard-model matter—we'll return to this soon), and what governing principles we must take into account in order to consider what mechanisms for motion are possible (relativity and quantum mechanics).

I quite like how philosopher Michael Redhead tackles this in his work.[4] He points out that there are two possible scenarios for how a particle moves. The first is that a particle moves from point A to point B, carrying what he calls its "individuality" along the way. This is the classical picture and it looks like Figure 12.1.

Figure 12.1. A particle transiting from point A to point B, imagined like a little billiard ball moving in a very classical manner.

The second scenario, shown in Figure 12.2, reflects the abstract point of view required by quantum mechanics. Here, something looks like a wave but it's localized, a bit particle-pointish. Its presence acts as an impenetrable barrier—a particle.

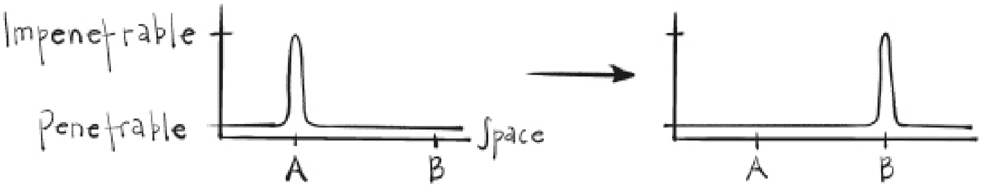


Figure 12.2. In this scenario, there is a region of space that is occupied by the particle and is impenetrable by other matter-like forms for that reason and then that region of impenetrability moves from A to B.

The illustration in 12.2 approximates the quantum-mechanical picture: The hump is a wave representing a particle localized around A, and that hump has characteristics that make the region more impenetrable than if the hump wasn't there, like the level that is labeled "penetrable."

The picture for quantum field theory invites an even stranger abstraction than this idea of a particle as "the impenetrable place." A cartoon version of it looks kind of like what's shown in Figure 12.3. Now we have a scenario where there is a manifestation of the particle at A. The particle is destroyed and then re-created at B as the wave relocates from A and manifests at B. One thing we know for certain is that there are rules governing the likelihood that the particle disappears entirely and never reappears. But beyond that, what Redhead points out is that the two quantum scenarios both seem like plausible interpretations of what is happening, and it's not clear how to empirically distinguish between the two or whether that's even possible.

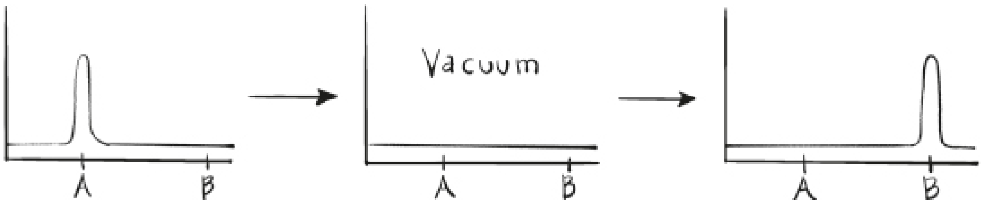


Figure 12.3. In this scenario, the particle again starts as an impenetrable region of space at point A. This time the particle is then completely disappeared and resurrected at point B.

It's clear that quantum field theory forces us to rethink the metaphors we use to talk about matter. What we used to think of as a reflection of our world turned out to be just the starting point of something much weirder. When we looked closely at the particle concept, we found ourselves stepping through a looking glass, into a universe full of quantum fields. As I drafted this section of the book, I found myself wondering: What is the point of a particle? Do we need them, conceptually? They seem so disconnected from how reality demands that we describe it. Quantum field theory is a useful calculational framework that is considered by many to be the most fundamental theory that exists in all of physics. It gives us an incredibly powerful machinery for creating models of phenomena that look and behave like matter. Which ones can we write down? On some level, the sky is the limit; our main boundaries are ones that we already know about. Symmetries, in particular, can be very important bounds on what the quantum field theory can be. Any mathematical term that transgresses the bounds of the symmetries gets thrown out. It's an incredibly elegant and fruitful way to build a physical theory.

But humans don't yet know how to figure quantum field theory into a social-linguistic framework that doesn't feel like a received mathematical abstraction. Think back to Aimé Césaire's reflections on poetry and science. He argued,

> The word increasingly risks appearing as an algebraic notation that makes the word intelligible. Just as the new Cartesian algebra has allowed the construction of a theoretical physics, so the original handling of the word can make a new science (theoretical and impartial), of which poetry can already give us a fairly good idea, possible at any moment.[5]

Césaire worried that we might turn language into a set of strict patterns and rules, without the ability to create myth. But what we see with quantum field theory is something that has a mythological element to it: While it describes something that is real, there is no translation into words that works conceptually, not fully. It turns out that even in physics, we are at risk of only being able to read notation, abstraction. And maybe this isn't a problem, but words are part of how we give the universe meaning. Somehow, the thing that we call strawberry emerges, conceptually, physically, and linguistically.

Quantum field theory may be our most fundamental theory, but we're still trying to figure out what it means. Plus, in 1998, astrophysics kind of broke it. That year, field theorists looked to the stars and said, "You've got to be kidding me."

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* And while I drafted this book, videos circulated on social media of ICE agents chasing undocumented people away from their daily work—picking food that feeds the whole country—in fields that may have been full of strawberries.

Go to note reference *

† For more on this, read the "Lost Identity: The Tale of Peasantry and Nature" by Asmaa Abu Mezied in the edited collection *Light in Gaza*.

Go to note reference †

‡ This is just one example, really. See Banu Subramaniam's *Ghost Stories for Darwin* for a whole book about this.

Go to note reference ‡

CHAPTER THIRTEEN

THE VACUUM WILL TEAR US APART

In which most of the energy in the universe is . . . not matter

It's 1997. Being a physicist means knowing that even when there is no matter, even when there is nothing, there is still something. That is some weird-ass shit, but it's something you are willing to accept—because, frankly, being a physicist means accepting that reality is super fucking weird. On the largest possible scales—cosmological distances—no one has ever successfully measured any kind of vacuum energy, even though quantum field theory suggests it should be there. Also there is a bunch of missing matter—all the visible matter is acting like there is extra matter out there, but you can't see it. This is annoying because your theory works so beautifully otherwise. But as a theoretical physicist, being annoyed is kind of your bread and butter. It keeps you up at night and gives you something to do during the day. You think about the fact that Einstein's equation can be modified to take into account a vacuum energy, but putting in the value you calculate doesn't match with observations, which again suggests there's nothing there.

Then, in 1998, a bunch of people announce that, well, actually, there is something that behaves like that modification to Einstein's equation. But it's tiny. So small that it's almost zero, except it is just big enough to cause a dramatic effect in space-time. The expansion of space-time is accelerating. Something is causing space-time to hit the gas so that the growth is progressively picking up speed as time goes on. The end result is that distance between galaxies is growing at an increasingly rapid pace—recalling the classic Joy Division song "Love Will Tear Us Apart." And it seems that this acceleration started fairly recently in cosmic history, kicking off for reasons that are completely unclear to us.

Goodbye, Galaxies!

In chapter 8, I described a moment in *Alice's Adventures in Wonderland* where Alice is confronted with a mushroom that will change her size. The reason that Alice is, by that point, so upset about her height is that she has already had some run-ins with size-changing consumables. In the first one, she eats a cake—because it said eat me and apparently one should always eat mysterious food when it instructs one to. The end result is portrayed beautifully in a John Tenniel illustration that accompanied the first edition of the book (see Figure 13.1). In it, Alice's neck is completely stretched out—a conceit to help the viewer understand that her body is in the process of changing size scales. The fact that Alice went from not growing to being in a state of growth means that there is a speed associated with her limbs and the speed is changing—they went from zero to . . . whatever speed Carroll imagined she was growing at. In other words, Alice's body parts go through a period of acceleration.

Figure 13.1. Alice "opening out like the largest telescope that ever was!" This drawing of a stretched-out Alice appeared with chapter 2, "The Pool of Tears," in the first edition of *Alice's Adventures in Wonderland*. This illustration appears on page 23 of Carroll, *The Annotated Alice: 150th Anniversary Deluxe Edition.*

For me, being a cosmologist means that whenever I look at Figure 13.1, I think about the expansion of space-time. We know that on cosmological scales, space-time is expanding. Like Alice is in the figure, different parts are being stretched away from each other. In the case of space-time, the way galaxies experience the stretching means that the farther they get from each other, the faster they seem to be going away. The parameter that characterizes this expansion is the Hubble-Slipher constant.[*] To first approximation, the Hubble-Slipher constant allows us to calculate how fast a galaxy appears to be receding from us based on its distance from us. As discussed in Dennis Overbye's *Lonely Hearts of the Cosmos,* measuring the Hubble-Slipher constant is a competition that has held the attention of astronomers for nearly a century now.

Key to making these measurements is figuring out how to measure distances when there is no measuring tape that we can roll out. Luckily, astronomers have been able to build something of a cosmic distance ladder using a combination of geometry and our understanding of stellar radiation. The seeds of this ladder were first planted by deaf Harvard College Observatory astronomer Henrietta Swan Leavitt, who realized there was a distinct correlation between the radiation patterns from pulsating stars known as Cepheid variables and how bright they are. The theory of electromagnetism allows us to translate this into a distance.[†]

Leavitt's period-luminosity relation works well for lighthouse-like stars and has allowed us to build out our distance measurement toolkit so we can measure lengths spanning deep into space-time. One of our best measurement tools turns out to be exploding binary systems of stars, a specific category of supernova, one way that stars die. Broadly speaking, supernovae happen with stars that are a bit more massive than our sun. Usually, what they leave behind is something that is like the core of the star but highly compactified—either a white dwarf or a neutron star.

White dwarfs can be roughly summarized as hot carbon-oxygenelectron balls: gravitationally bound collections of carbon and oxygen, side by side with a bunch of free electrons. They are very dense—more than 100,000 times denser than the planet Earth. And they can have anywhere between half the mass of our sun to 133 percent of the mass of our sun, so they also pack a gravitational punch. If one of them gets near a star, as happens occasionally, that's it for the star—the white dwarf starts slurping up the star, taking on more and more until the white dwarf heats up to the point of setting off a runaway nuclear chain reaction, with carbon fusing into heavier elements. Boom! The uncontrolled nuclear reactions become an explosion, a supernova. This particular type of supernova due to a white dwarf and a companion star is known as Type Ia.

The neat thing about Type Ia supernovae is that they have extremely predictable light spectra shapes. Every Type Ia supernova has roughly the same brightness over time as every other one. This is because they have the same engine—fusion of lighter elements into nickel. Nickel fusion as the reason for the source of the Type Ia supernova light curve shape was first proposed by Titus Pankey in his 1961 doctoral dissertation, the first PhD in physics from historically Black Howard University.[1] The shape is useful to cosmology because looking at where the shape peaks—what color it centers on—can help us measure redshift. Recall that measuring the redshift using a spectrum is one way we can measure actual distance. Because the shape of a Type Ia light curve is always roughly the same, the only thing that changes is how far into the red it is. The redder it is, the farther away—the more redshifted. The Type Ia supernova, in other words, is a cosmic measuring tape. In 1998, two separate teams of astronomers observing Type Ia supernovae for the purposes of trying to better measure the Hubble-Slipher constant announced something truly incredible: Like Alice's neck when she eats the strange cake, the expansion of space-time is accelerating.

This is to say, if we return to the visual metaphor of the balloon (Figure 4.1), we now must imagine that the balloon is stretching faster and faster, with the distance between the galaxy-like dots on it increasing at an ever more rapid pace. The prospects are potentially a bit bleak. This means that there is a future where most galaxies may be so far away from each other that they are behind each other's cosmic event horizons (see chapter 4 for a reminder of what these are). The good news is that this future will arrive long after our sun dies and destroys the Earth in the process—and that's at least 4.5 billion years from now.[*]

The prospect of a universe where we are isolated with only our local galactic neighbors is far from the most stressful problem associated with this new information, however. We now have a cosmic acceleration problem: The expansion rate of the universe is increasing and we don't know what's causing this change. We can fairly easily account for it in general relativity by treating cosmic acceleration as a measure of what we call the cosmological constant, or general relativity's version of the vacuum energy. It's very easy to adjust Einstein's equation to reflect this: just input a vacuum energy and solve the differential equation again. But general relativity doesn't help us understand how we might calculate the value of this vacuum energy. It is agnostic about the value of the cosmological constant—or whether it's even constant.

Because it's possible that the vacuum energy that drives cosmic acceleration might be changing in value, there is a general term for it—dark energy. I always get asked about this, so let me start here: The only thing dark matter and dark energy have in common is that we have never directly observed them, just like Wu-Tang Clan rapper GZA's long promised but never arriving *Dark Matter* album. Because they are invisible, they've both got the word "dark" in the name. Otherwise, dark energy is a completely different beast from dark matter (a phenomenon I will discuss further in the next chapter).

I don't like using the term "dark energy" when we could be calling it the "cosmic acceleration problem" instead, though I get that the latter is less rhetorically pretty. But the only reason the phenomenon is called "dark energy" is because "dark matter" was already a concept out there in the world. The work that the word "dark" is doing, in both terms, is as a container for our ignorance. It's a way of saying, "Here's a thing we don't know about, but we know it's happening."

The story I'm telling you about an accelerating expansion of space- time might feel familiar. That's because in chapter 4, I described inflation during the Hot Big Bang era—a period when a particle called the inflaton caused the expansion of space-time to happen exponentially, for a very short time. Late-time cosmic acceleration is very much like this, except that the increase in pace is a lot slower than during the inflationary era. But naturally this invites us to ask the question of whether there is a similar source. In the case of inflation, we have to add a new field. Dark energy (or the cosmological constant) is more of the same, but now we can connect it to what we know about how the vacuum works in this phase of the universe.

There's an obvious solution to this problem: Surely the dark energy is also a contraption made of nothing (albeit a simpler one than a complex structure like you). I mean that it seems natural to expect that, since general relativity doesn't say much about calculating the vacuum energy and quantum field theory has a bit to say about it, the dark energy must be whatever quantum theory says it is. The only problem? The vacuum-energy value that is needed to explain cosmic acceleration is extremely, inexplicably small. It does not match the values predicted by the flickering of the vacuum in quantum field theory, or any of the known extensions to it.

And this is not a minor problem either. One thing we can extract from solving Einstein's equation is that whether the vacuum energy is constant or not, it appears to be the dominant form of energy in our contemporary universe. It outnumbers stuff we might call matter (see the next chapter) by more than 2 to 1—it's approximately 70 percent of the apparent matter-energy content in the universe. In the end, every particle type we have ever seen comprises a very small fraction of what appears to be out there. And whatever is driving cosmic acceleration doesn't behave like matter in any obvious way—instead, it behaves like a vacuum energy that is literally pushing space-time apart. The best way to have intuition about this is to think about how humans breathe. I think colloquially we tend to believe that when we inhale, we pull air into our noses, like our noses are swallowing air. This is how frogs breathe, but it's not how humans do. Instead, we humans pull our diaphragms down, which opens up our lungs. This creates a negative pressure gradient between what's outside our bodies and our respiratory system. This difference in pressure makes air rush into our respiratory system through our noses. Similarly, the vacuum energy behaves as a source of negative pressure for space-time.

My So-Called Invisible Universe

This idea of an inexplicable negative pressure pushing space-time onward and outward changed my life. In December 1998, I glued a cutout (see Figure 13.2) from a January 1999 *Scientific American* feature about cosmic acceleration onto my application to the California Institute of Technology (Caltech) and wrote, "I want to solve this problem."[*] The figure itself focused on three possible scenarios: constant expansion of space-time, decelerating (slowing down) expansion, and accelerating expansion. These are all different versions of the Alexander Friedmann solution to Einstein's equation, which I first mentioned in chapter 3. Depending on which scenario we are in, the age of the universe and the timing for events like galaxy formation will be different.

Each scenario has the potential to tip the fate of the universe too. Since matter's relationship with gravity is typically Newtonian, it has the tendency to pull space-time inward. Too much matter or energy? The universe collapses in what is sometimes called the Big Crunch. This is more likely to happen in a deceleration scenario, where the expansion is slowing down, making it easier for matter to do space- time in. The rate of deceleration will determine how much matter is needed for this to happen. In the constant-expansion scenario, the fate of the universe depends entirely on how much matter there is. Too much? The universe is toast. In the accelerating scenario, space-time gets more of a fighting chance against the pull of matter. In this sense, cosmic acceleration is space-time's engine, driving it forward.

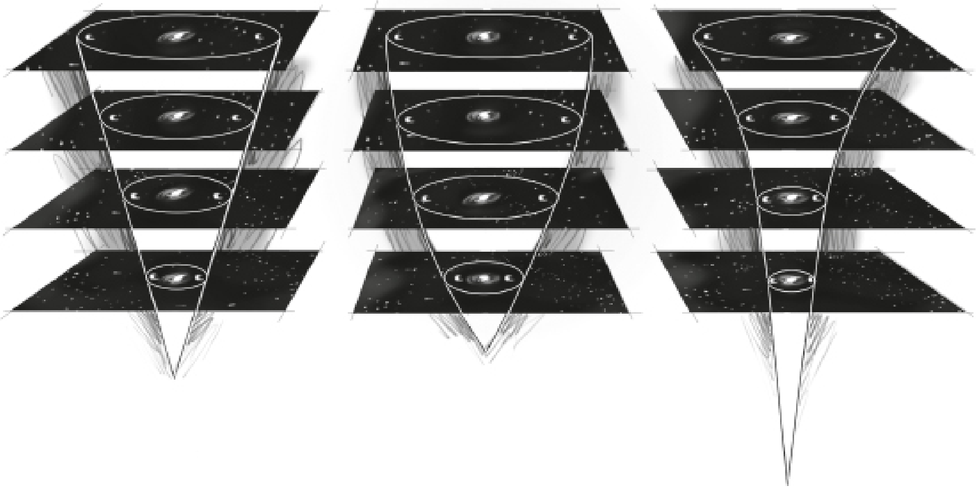

Figure 13.2. The *Scientific American* caption that appeared with this figure explained that there were three possible "patterns" for cosmic expansion. On the left, we see the constant scenario. In the middle, we see deceleration. On the right, acceleration. Time is passing vertically, and you can see that how time passes will be different for each scenario, with the accelerating universe getting older faster than the decelerating and constant universes.

So one interpretation is that dark matter and dark energy are indeed linked, by the way they work against each other. It happens to be that in our case, they seem to strike a fine balance. There is just enough dark energy to keep the universe's expansion accelerating, but not so much, at the moment, to indicate that we are in the most dramatic scenario, a runaway universe that is extremely bent out of shape. And I really do mean shape. These questions of how much stuff there is inside the universe—how much matter, how much energy—determine the actual shape of the universe. There are three possibilities: no curvature (flat), positively curved, and negatively curved (see Figure 13.3). In the flat space, two ants walking along initially parallel paths will remain in parallel formation forever (return to Figure 3.2 for a visual). In the positively curved scenario, the two ants would eventually run into each other. In the negatively curved scenario, their paths will eventually diverge away from each other, no longer parallel.

It happens to be the case that our particular balance of cosmic acceleration and matter appears to have landed us in the flat situation. Seriously! Despite superficial appearances, this is still a result that uses the fact that space-time is shaped by matter and energy. Think about the ants on their parallel lines. On a piece of paper, the lines stay in the same location forever. By contrast, cosmic data says that in our flat space-time, the lines may stay in parallel, but as space-time expands, the distance between them grows. Even in our flat universe, matter and energy are still telling space-time how to move: The amount of dark matter and dark energy in space-time have created this outcome, which would not be possible in a universe governed by special relativity or Newtonian physics alone.

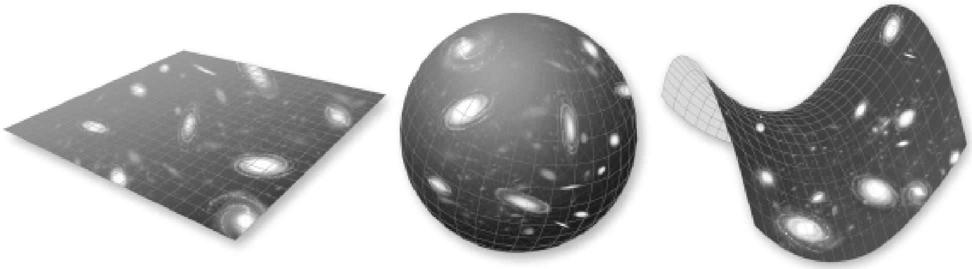

Figure 13.3. Left to right: Flat, closed, and open universes. Artwork showing the geometrical curvatures of a “flat” (left), “closed” (center), and “open” (right) universe. The curvature of a space-time is determined by the amount and density of matter and energy inside of it, as well as a possible fundamental curvature. In an open universe, the amount of matter can't

counterbalance expansion, which will go on forever. In a closed universe, there is enough matter to stop expansion, leading to the Big Crunch. In a flat universe, the amount of matter is perfectly balanced between these two extremes, and expansion will continue but without warping the shape of space. Of course, these are low-dimensional schematics, since our actual space-time is four-dimensional. In this figure, we can't see the extra spatial dimensions or expansion in time.

For twenty-six years, I watched and waited for a surprise that would suggest that maybe things were more complicated than that. In the interim, I chose going into debt at Harvard over a full ride at Caltech (so maybe I don't have the best judgment), and I did not solve the problem of what causes cosmic acceleration. But in my defense, no one has. I wrote my PhD dissertation about how the existence of dark energy, as the cause of cosmic acceleration has come to be known, suggests that the mismatch between the measured vacuum energy of cosmology and the predicted vacuum energy of quantum field theory is our first ever observed quantum gravity phenomenon.[2]

In hindsight, this was a fairly decent take, although I couldn't have written those words two years ago. Science can be surprising. For years we wondered about the possibility that the cosmological constant was variable —not actually constant. This is really where the terminology "dark energy" comes to life. Maybe there is a variable vacuum energy that changes value as time goes on. As a PhD student, I spent a lot of time thinking about this. But at the time there weren't any indicators from the data that dark energy changed with time. In March 2025, while I was working on the third draft of this book, that all changed. The Dark Energy Spectroscopic Instrument (DESI) collaboration announced that they had detected the first ever evidence that dark energy had a different value in the past. Only time will tell whether this result holds up, but if it does, 2025 will be a year cosmologists remember for a very long time, and not just because the Trump administration did its best to slash and burn science funding.

The Edge of Space-Time's Expansion

There are so many reasons it would be a real shame for the leaders of the U.S. government to (undemocratically) collapse the scientific research infrastructure that Americans have spent decades investing in, though as I finalize this manuscript that seems to be what's happening. Besides all the obvious impacts on public health, one reason this is a travesty is that we are actually in a terribly exciting moment for cosmology, even if we ignore the cosmic acceleration problem. Over the last few years, it's become clear that we now also have another, ongoing problem with cosmic expansion: Observations over the last decade seeking to better quantify the value of the Hubble-Slipher constant don't agree with each other. The Type Ia supernova observations are completely out of sync with the number estimated from fitting the CMB power spectrum data to the theory. Astronomer Wendy Freeman, who has led a team making the same measurements using a type of star known as tip of the red-giant branch (TRGB) stars, has proposed that the problem is we don't understand how to use our distance markers as well as we thought. This Hubble tension is, as of now, unresolved, and possibly harder to explain than cosmic acceleration because any adjustment breaks cosmological theory that otherwise works quite well.

One proposal, put forward by Vivian Poulin, Tristan L. Smith, Tanvi Karwal, and Marc Kamionkowski is that something called "early dark energy" could solve the problem.[3] In this scenario, dark energy would start having a notable impact on space-time much earlier than in our standard narratives, during the early universe era. Kamionkowski explains in an interview, "Early dark energy is a class of models in which the early expansion history of the universe is altered through the introduction of some new exotic component of matter that we call early dark energy."[4] The timeline of space-time's evolution is altered by early dark energy in a way that could make the CMB power spectrum's tension with other data dissipate.

What I'm pointing to here is that the solution to the cosmic acceleration problem may also solve the Hubble tension. There are other ways of addressing cosmic acceleration, of course. One idea, which I reject, is that all values for the cosmological constant are possible, and we just happen to live in the part of the multiverse with the value that it has because otherwise we wouldn't exist. I'll discuss later why string theorists are fond of this idea, which is sometimes identified as the anthropic principle. My feeling about it is: Thanks, I hate it (and I'll say more about why in chapter 16).

Assuming anthropics aren't the solution (and I grudgingly admit they might be), then we have to go looking for evidence that cosmic acceleration really is caused by a dark energy—a quantum field that changes with time. There are a series of new astrophysical experiments tasked with searching for evidence of this possibility, which hopefully will build on the promising announcement from DESI. The week I began working on this book, the European Space Agency's Euclid telescope launched to its home at the second Lagrange point, a stable orbital position that is well past the moon. Euclid is looking at the distant universe using visible and infrared light with the explicit goal of understanding how dark energy may have changed over time and how dark matter shapes galaxies.

As I was finalizing this book, the Vera C. Rubin Observatory—the one with the biggest camera in the world—took its first images from the Chilean Atacama Desert.[*] They're magnificent, and you should look them up—they're all online for free thanks to public funding from governments around the world. Rubin Observatory will do a wide variety of science, and it has a very active Dark Energy Science Collaboration (DESC). I became a member of DESC when the Dark Matter Working Group, of which I was a founding member, became one of its units. I'm hella excited about it. DESC will, like Euclid, be looking for evidence of changes in dark energy and how it shapes space-time.

And they won't be alone: Soon after this book comes out, NASA's Nancy Grace Roman Space Telescope will launch (unless the Trump administration gets its way and manages to cancel the project). Roman and Rubin have so much overlap that we already have teams working on developing the pipelines for simultaneous data analyses and combined data sets. Rubin is responsible for making dark matter a major problem in contemporary physics and astronomy (see the next chapter). I love the idea that her name will live on in an observatory that will continue to carry out her scientific mission. Well into her eighties, she told me she still regularly went to her office at the Carnegie Institution. She was the first person to ask me, a young nobody graduate student, how to solve the dark-matter problem.[*] That same day, she introduced me to Nancy Grace Roman, the infrared astronomer who is known as the mother of the Hubble Space Telescope.

Roman and Rubin the scientists are no longer with us. But for the next decade, they will be two of our guiding photon collectors. I don't hope that they will provide us only with answers. Rather, I hope that they will have us asking new questions about an ever-surprising universe.

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[*] For an interesting discussion of why this should be called the "Hubble-Slipher constant" rather than the more common "Hubble constant," see: MacDougal, Marcus, and Bartusiak, "Is It Time to Rename the Hubble Constant?"

Go to note reference *

[†] For more on Leavitt and her work, see: Sobel, *The Glass Universe*.

Go to note reference †

[*] See the *Wandering Earth* films for a novel imagining of how humanity might deal with this problem.

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[*] The article was Kirshner, Hogan, and Suntzeff, "Surveying Space-Time with Supernovae: Exploding Stars Seen Across Immense Distances Show That Cosmic Expansion May Be Accelerating." You can read the article using a subscription (your local library probably has one!) to *Scientific American*. One of the coauthors, Robert Kirshner, was ultimately the first astronomer I ever approached for a job. For two years as a federal work-study student at Harvard College, I earned my weekly spending money preparing raw Hubble Space Telescope images of supernovae for data analysis by Kirshner's team, under the supervision of Peter Challis. I got the job by emailing Kirshner during the summer of 2000 and telling him I found his supernova work to be interesting. Maybe cheeky, but it got my foot in the door.

Go to note reference *

[*] Also, while I was finalizing this book, I was one of the many queer scientists involved in Rubin Observatory collaborations who was deeply hurt and impacted by the observatory leadership's swift moves to satisfy the Trump administration's demands to erase the visibility of queer people and queer spaces in science. I wrote the sentence in the text before those moves in February 2025 happened. Vera Rubin, who was Jewish, was a lifelong advocate for women in science. The observatory also modified her public biography to tone down the emphasis on these values. Collaboration with fascists only advances fascism.

Go to note reference *

[*] To learn more about Vera Rubin, check out Mitton and Mitton, *Vera Rubin,* and Yeager, *Bright Galaxies, Dark Matter, and Beyond*.

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CHAPTER FOURTEEN

ALL THAT WE MAY NEVER SEE

In which we are all the 4 percent, but most of matter isn't

We may be abstract contraptions made of nothing, and most of the universe may be full of an energy that, frankly, has no business being thought of as matter (Einstein's matter-energy equivalence be damned), but we are not nothing. As shown in Figure 14.1, we are the 4 percent, which is to say that everything we might term as "normal" matter or "visible" matter is a small but precious (to us, anyway) fraction of what populates the universe. We—the stars and the people—are a queer feature of the universe, a rare manifestation of cosmic energy.

To look at the universe is to see not just visible matter but also what's missing. We see dark matter through the looking glass of visible matter. The missing-matter problem has been a wonderful canvas for the theorist's imagination and a thorn in the experimentalist's side for decades. If we're just counting matter and completely ignoring pesky vacuum energy, dark matter is about 85 percent of the matter in the universe. It's everywhere, but we can't look at it. Most galaxies and galaxy clusters are full of it.[*] Together, dark matter and dark energy comprise almost all of what's inside of the universe. That we know this is a significant accomplishment. The only problem is that we have no idea what either of them are. And to have any chance at understanding them, we need to understand what we are looking at in the first place.

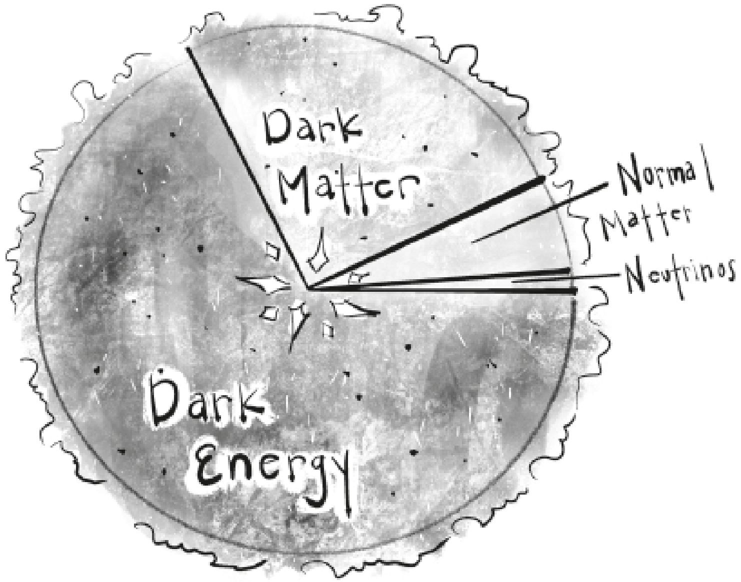

Figure 14.1. A pie chart showing the rough breakdown of the energy-matter content in the universe. This one breaks out neutrinos separately from "normal matter." They are so hard to see that they're almost invisible matter.

All That We Have Ever Seen

The crowning triumph of the quantum field theoretic perspective is known as the standard model of particle physics, which describes every particle we've ever seen, touched, or somehow observed directly in a laboratory, as well as how they all interact with one another. The whole thing—including the relationships between particles—is summarized in Figure 14.2. Notably, the top row includes all of the elementary particles that we are made of—electrons and two types of quarks, the up quark and down quark.

The electron is part of a family known as leptons. The leptons include two other particles with a charge of −1 like the electron: the muon and the tau (or tauon). Every charged member of the lepton family has an uncharged companion known as a neutrino—that is, an electron neutrino, muon neutrino, and tau neutrino. Neutrinos and their antimatter counterparts, antineutrinos, are strange little creatures. They have a wee bit of mass, but not much—and our standard model, while brilliant, is unable to explain their mass. As they travel through space-time, neutrinos transition from one type to another, apparently at random. A neutrino that starts out as an electron neutrino can randomly become a tau neutrino, and so on—which is to say that neutrinos are non-trinary and their identities are not fixed. We do not currently understand the mechanism that drives these neutrino oscillations, but we think it's related to what causes the neutrinos to have mass. Think about it: There are non-trinary neutrinos flying freely through space, unmolested by any human assumptions about whether their identities *should* be fixed or not.

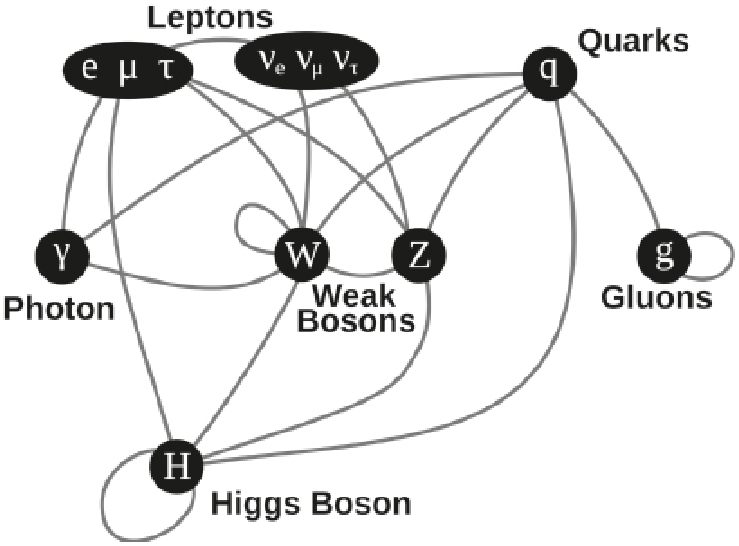

Figure 14.2. The Greek letters in the lepton category represent different particles: e for electron, μ (mu) for muon, τ (tau) for tauon, ν (nu) for each neutrino. All of the standard-model particles are connected by lines which indicate their interactions. These particles comprise only 4 percent of cosmic energy.

Neutrinos are not the only type of particle that display an inherent diversity. There are actually six particles in the quark family. Besides the up and down, we've observed four others in particle-physics experiments: top (or truth), bottom (or beauty), strange, and charm. All quarks have partial electric charges that come in multiples of ⅓. Electrons and quarks also have antiparticles that have the exact same properties as the original, but with the opposite charge sign. These fall in the category of "antimatter." The electron's antimatter counterpart is the positron, which has a positive charge. Importantly, these particles have the same mass because, as I explained in chapter 6, there is no anti-mass. Quarks and anti-quarks can join together to form short-lived particles called mesons. You never experience these directly, but they can be made in high-energy particle collisions. They were almost certainly prevalent in the early universe. Importantly, some mesons are nonbinary: They can oscillate between types, much like non-trinary neutrinos.

Our first quantum field theory, the photon, is on the second row of Figure 14.2. This row is special. Importantly, electromagnetism is not just the theory of light. It is also the theory of the electromagnetic force. So photons are the particle associated with the electromagnetic force—what we call a force carrier. Thus, the matter components of the standard model of physics—the top row—are joined by what we call the force mediators: the familiar photon, which mediates electromagnetic interactions; gluons, which mediate the strong nuclear force; and W and Z bosons, which mediate weak nuclear force interactions.[*] Gluons essentially glue or hold together the quarks that make up protons and neutrons.

Gluons' strong nuclear force is incredibly powerful, more than 100 times stronger than the electromagnetic force and 10^{38} times stronger than gravity.[†] But unlike those two forces, the strong nuclear force is only effective over an extremely short distance, across something roughly the size of a composite particle like the proton. And the energies involved with the strong nuclear force are very high, suggesting that special relativity is important. Taking matter-energy equivalence into account helps us understand that most of the mass of the proton and neutron, each composed of three quarks, is not actually due to the mass of the quarks. Instead, most of the mass from these quark composites—a category known as the hadron—comes from the gluing energy associated with the presence of the gluon.

The strong nuclear force is 10^6 times stronger than the weak nuclear force, which functions quite differently from the strong. The easiest way to understand the weak nuclear force is through what it *does,* which is nuclear decay. In nuclear decay, there are neutrino emissions—and transmutations of neutrons and protons into each other. The W and Z bosons facilitate these processes by changing an up quark into a down quark or the reverse. A proton has two up quarks and one down; flip an up quark into a down, and the proton becomes a neutron. Flip a down quark in a neutron to an up, and the neutron becomes a proton. This particular behavior is important in the astrophysical formation of heavy atomic elements such as carbon, oxygen, and even gold. In other words, the ancients' obsession with alchemy, which now seems laughable to us, wasn't completely wrong! Sometimes science really is magic, just doing things differently than we imagined in our lore. We can't get a strawberry without nuclear decay! Nuclear decay is also a safe part of everyday supermarket life: The potassium in bananas is in a continuous state of nuclear decay, which means bananas are a very minor source of neutrinos.

At extremely high temperatures, like $10^{15°}$ F or C, the electromagnetic force and weak force are unified. The last time anything in the universe was that hot was during the Big Bang era. Thus, the standard model of particle physics is in fact cosmology—because it tells us something about how the timeline must have unfolded for particles and the forces that govern them. The only Muslim to ever win a Nobel Prize in physics and the first in science, Mohammad Abdus Salam, won alongside Sheldon Glashow and Steven Weinberg for the discovery of this Electroweak Unification.[*]

There is an interesting division in the standard model that might just seem like a quirk of how Figure 14.2 is drawn. As you can see, leptons and quarks are on one line; photons, W and Z bosons, and gluons on another; and below that, we have the Higgs. There is a fundamental division at work here: The leptons and quarks are all fermions, and the rest are all bosons. The distinction between fermions and bosons? Spin. Fermions are particles that have a spin that is a multiple of 1/2. Bosons have a spin that is a multiple of 1, a whole number with no fraction. And these spin properties have far-reaching results: Fermions in a quantum system cannot share the same quantum state, while bosons can all be in the same identical state. This explains the electron orbitals in atoms that we all suffer through learning in chemistry because they don't teach us quantum mechanics first—electrons cannot all be in the same orbital state, and the orbital rules are just the implementation of this property (known as the Pauli exclusion principle).

This knowledge is another gift of the photon. Bengali scientist Satyendra Nath Bose first arrived at the idea that photons are bosons because he wanted to explain the mathematical form that Planck's law for blackbody radiation took. Getting his idea into the scientific literature involved calling in a favor. Bose had translated Einstein's relativity papers into English for readers in Calcutta. To get his idea published in German, the scientific lingua franca of the time, he wrote to Einstein and identified himself as the translator. He asked if Einstein would consider the scientific ideas, and—if he agreed with them—translate the paper from English into German and facilitate its publication in a German science journal. Einstein came through and helped bring the world Bose's 1924 paper "Planck's Law and the Hypothesis of Light Quanta." At the time, the circulation of new scientific ideas, especially for scientists in the colonies, depended on this kind of mutual collegiality.

The fact that we know so much about the standard model is hard- won, mostly from thousands of people working together on experiments that collide particles together at high (relativistic!) speeds to see what happens when they break apart. These experimentalists work in tandem with theorists, people like Mary K. Gaillard and Benjamin Lee, who together predicted the mass of the charm quark, giving experimentalists something to aim at.[*] But in addition to what causes neutrinos and some mesons to oscillate, there's still a lot that we don't know. Particle physics is not complete. For instance, we have no idea why we live in a universe where most of the visible matter-like stuff is matter, rather than antimatter. Antimatter and matter have a kind of explosive relationship: They cancel each other out when they come into contact. So you might imagine this would cause problems in the early universe if there were an even amount of both, causing all matter to cancel itself out, leaving us with nothing. But instead, there is something. Work on this question at the intersection of particle physics and cosmology is lively because it goes to the heart of a question I touched on in chapter 4: How exactly did particles emerge from the end of inflation?[*]

We are also still asking big questions about whole classes of particles. Bosons especially continue to be a matter of great curiosity for scientists. Consider the particle that stands alone in Figure 14.2 and in the standard model: the Higgs, which is thought to give the other massive particles—except neutrinos—their mass. The Higgs is the newest particle to us, observed for the first time in 2012. We are still in the early stages of fully understanding it. Like the photon, W, Z, and gluons, it is a boson, but unlike any other fundamental particle it is a boson with spin zero. It has *no* quantum spin! Until we observed the Higgs, we weren't sure that any spin-zero elementary particles existed in nature. Now that we know the Higgs exists, we wonder: Is it alone?

A particle-only perspective is not intellectually expansive enough for the idea of the Higgs boson. The Higgs is an example of a particle that was first conceived purely from a quantum field theoretic perspective. And without the Higgs, we wouldn't have an explanation for why any of the particles in the standard model have mass. Today, we can say the fundamental particles that comprise us all gain their mass from the Higgs mechanism—which is to say that we are all made of particles formed from quantum fields acting on the vacuum, which gain their mass from the Higgs field, which is active in the vacuum.

All of the particles we have ever seen—electrons, photons, Higgs, and so forth—are governed by a quantum field theory, but not just any quantum field theory. We know that the speed of light is finite and special relativity applies. In other words, we know that any model describing particle physics must account for Lorentz invariance—namely that the rules of physics are the same for all observers in the same frame. Lorentz invariance is an example of a symmetry, a concept I first introduced in chapter 5. Symmetries like Lorentz invariance play a key role in what makes our specific quantum field theory work the way it does and arrange the visible universe the way it does. Instances when our universe doesn't obey symmetries also help explain why the visible universe is so diverse.

Consider Alice going through the looking glass. Of course she would expect that the rules of that universe would be the same as the one she exited, except perhaps left becomes right and right becomes left—everything should be a mirror image, right? In physics, this idea that the laws of physics would behave the same in a mirrorverse is known as parity symmetry. Experimental work shows that electromagnetic interactions and strong nuclear interactions between particles obey parity symmetry: put them in a mirror and they will behave exactly the same, just with left and right reversed.

Of course, anyone familiar with *Through the Looking-Glass* might remember that what Alice finds there is a very different world from the one she left behind. The rules there are different! In 1956, Tsung- Dao Lee and Chen Ning Yang proposed that this might be the case for parity symmetry—at least for weak nuclear particle interactions.[*] They weren't sure how to prove it, though. The person who resolved the problem was Chien-Shiung Wu, who you might remember also designed experiments that became the foundation for future research into entanglement (described in chapter 9). Leading a multiinstitutional team, Wu used magnetic fields to study how radioactive cobalt emitted high-speed electrons and positrons, known collectively as beta particles.

Wu was specifically interested in beta particles that were emitted in the same direction as the cobalt's spin. In a world where going through the looking glass meant everything stayed the same, we would expect that the same number of particles would be emitted in the direction of the spin *and* in the opposite direction. There's no reason for that symmetry to be broken. What Wu and her team found was that more particles were emitted in the direction that was opposite of the cobalt atom's spin than in the same direction of the spin. In other words, particles engaging in weak nuclear interactions had a sense of the difference between left and right—going through the looking glass does not yield the exact same behavior. If you look carefully at Figure 14.3, you can spot the difference.

Figure 14.3. This linocut by Ele Willoughby portrays an apparent mirror image of Chien-Shiung Wu. I say "apparent" because if you look closely, the image of the circuit she's holding has the "N" and "S" flipped from top to bottom. This is a visual representation of how Wu's experiment showed that parity symmetry was violated: Left and right are almost identical, but not exactly.

This all sounds very abstract, and also, this is us. We are what we ourselves perceive as incredibly abstract phenomena come to life. The vacuum is never empty, and it contains the stuff of all life. The fact that weak nuclear force interactions between particles can display a fundamental difference between left and right means that there is always a way to communicate the difference between the two, at a cosmic level. A deep understanding of nuclear and particle physics—of our quantum field theory—gives us a way to orient ourselves in space.

1970

The standard model is awesome and everything, but it is not the end of the conversation about matter in the universe. For a long time, people thought the contents of the standard model were all they had to factor into the "matter input" for the equations that govern general relativity. And frankly, when I began this chapter, I could have started by making the claim that even today space-time is mostly empty, but whether I'm telling the truth is, to some extent, a matter of perspective. When we look outward beyond our atmosphere, we see a cosmos replete with voids—apparently empty space with nothing inside of it. The shapes and distributions of these voids throughout the universe are quite useful because they sometimes tell us information about the shapes of galaxy clusters and other objects that are decidedly filled with "stuff" and not at all empty. But it's also the case that, as you learned earlier, space-time contains leftovers from the early years—the cosmic microwave background radiation—in the form of light that is invisible to the human eye but very visible to instruments tuned to "see" microwave. So whether space-time is empty or not is a matter of perspective, and if we are not careful, this can be socially determined by our own limitations.

The technology that we use to look at the universe can transform the boundaries that exist around our sensibilities of what's "out there." For example, if we look at how fast stars are orbiting their galactic centers, we can use that speed to calculate how massive we expect a particular galaxy to be. Given the speed information, that calculation can be done by anyone who remembers college Newtonian mechanics. There's no reason to think relativity or quantum mechanics come into play, so we should feel fairly confident in this calculation, right? And we can also check our work by adding up how much light is coming from stars, gas, and dust in the galaxy; the amount of light directly corresponds to how much mass there is, because stars are nuclear mass-to-light conversion factories. The amount of light from gas and dust can also be translated to an assessment of how much there is of either. We would expect that the mass measurement based on light output and the mass measurement based on star rotation speeds will match.

But they do not. Beginning in February 1970, Vera Rubin and Kent Ford published a series of papers showing that the mismatch was significant. Rubin, using an instrument developed by Ford, collected data about the speeds at which stars orbited their galactic homes. What they found was that the stars were going faster than one might expect based on a mass extrapolated from the amount of light radiated. In other words, the stars were moving like there was a matter presence that wasn't radiating light. This was the first substantive evidence for the existence of a substance first hypothesized and named dark matter by Fritz Zwicky in 1933, or what Nobel laureate P.J.E. Peebles has come to call subluminous matter.[*1]

In my previous book, I wrote extensively about how misunderstandings can arise when we are not thoughtful about the metaphor invoked by referring to dark matter as "dark" matter.[2] And this raises interesting questions about the metaphorical challenges of how to name what we are witnessing when light appears to be absent. Naming is a process of seeking out language that can illuminate abstract concepts we want to make more accessible and communicable. This requires communicating via ideas that are already familiar to us as a species. Another challenge in this case is that "dark" and "light" have specific cultural connotations. Within the analytic frameworks of Western European nations and their former settler colonies, "dark" tends to be associated with evil and generally connotes "less good than light." This is inextricably tied to the ugly and continuing legacy of scientific racism, which is unfortunately not a thing of the past.

Whether "dark matter" is the best possible name, we are currently stuck with it—until we know what exactly it is. And I should point out that, technically speaking, what really happened is that Rubin and Ford found evidence for a mismatch between Newtonian gravity and observation. There are two ways to interpret this. The first is to say, "Ah, there's matter that we didn't know about because it doesn't seem to radiate light in any frequency."

That's where most of us have landed. There's a second option, though: Maybe our whole theory of gravity is wrong—in a regime where it should work perfectly well. A very small portion of the physics community pursues this idea, broadly known as modified Newtonian dynamics (MOND).

The problem that MOND continuously faces is that Rubin and Ford's galactic rotation curves are not our sole or even best evidence for the existence of dark matter. This includes phenomena you've already met before. The first is gravitational lensing: The most spectacular gravitational lensing effects you will see due to galaxy clusters are not only from the visible matter but also from the invisible dark matter in the clusters. We can even use observations of gravitational lensing to reverse-engineer and figure out where the dark matter must be.[*]

Our best evidence for the existence of a new type of matter—what we call dark matter—is thanks to our old friend, the cosmic microwave background radiation (CMB), the light that's been traveling through the cosmos since around 380,000 years after whatever happened when cosmic time was zero. One of the key measurements of the CMB is something called the power spectrum, a measure of how much power there is in the CMB temperature fluctuations across different length scales (see chapter 11 for a reminder about CMB details). In other words, this is a measurement of the strength of the fluctuations in relation to spatial distances.

We have been able to measure this power spectrum in extraordinary detail. To compare theory and the observations, we assume the existence of a dark-matter contribution comprising 26 percent of all the matter-energy in the universe. And the incredible thing is that this assumption makes the power spectrum predictions match observations perfectly. You can see this in Figure 14.4, which shows the data as points with a line that's predicted from theory. What you can see is that the data fits on the line perfectly and the error bars are extremely small on the data for scales where the Milky Way doesn't interfere with observations (on the far left). This is the best match between data and theory in all of physics, as far as I know.

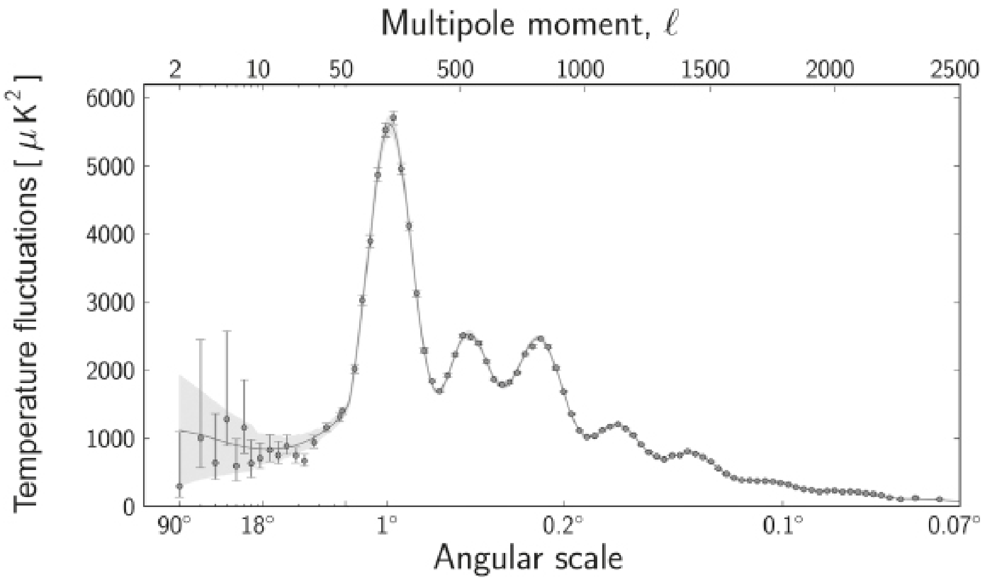

Figure 14.4. The 2013 CMB power spectrum from the most recent major CMB experiment, the Planck Telescope. The vertical scale is the amount of power in temperature fluctuations, as in how big the fluctuations are. The horizontal scale across the bottom characterizes the length scales involved. The "multipole moment" across the top is another way of characterizing length scales in a coordinate system based on the sphere. The points are data; the line through them is theoretical prediction.

Today we have a pretty good (if not fully fleshed out) sense of how dark matter shapes the universe we see. I like to tell people it's like the invisible nonbinary person in Figure 14.5, also known as The Invisible Enby. We can't see a face or any anatomy at all, but there's a hat in about the right spot and a suit that is filled in. We have every reason to believe the Enby is there, because the visible suit is observably hanging off of their body. The relationship between dark matter and visible matter is a lot like this—we know that galaxies are dominated by dark matter because of how matter moves in them, even though we can't directly look at the dark matter itself. Visible matter is the discernible edge of dark matter's invisible presence.

It seems that most galaxies, if not all of them, exist inside a larger invisible dark-matter halo that stretches from the center of the galaxy to well beyond the visible part. Large galaxies like the Milky Way and our neighbor Andromeda also have satellite galaxies that are gravitationally bound to it somehow (two of which you saw, in Figure 11.3). The Milky Way has several, perhaps as many as sixty. Each of these satellite galaxies has its own little dark-matter halo, a dark-matter subhalo. On the largest scales, dark matter and visible matter together trace out a cosmic web that we can simulate with large computers. One famous example of a simulation that shows the dark-matter side of this web is the Millennium Simulation, pictured in Figure 14.6.

Figure 14.5. The Invisible Enby.

So, dark matter is out there, leaving us with a challenging question: What is it? We know that it interacts gravitationally with what we tend to call visible matter—matter that somehow interacts with other standard-model particles. We know enough about the standard model of particle physics to understand that, whatever dark matter is, it's *not* any of the particles that we've observed in the laboratory. We know that it doesn't interact with light at observable levels. We know that it seems to be invisible or transparent, in that it doesn't absorb light. Based on its gravitational interactions, we know it outnumbers visible matter at about a 5-to-1 ratio, meaning that visible matter, the stuff we are made of, is only about 4 percent of the matter-energy content of the universe.

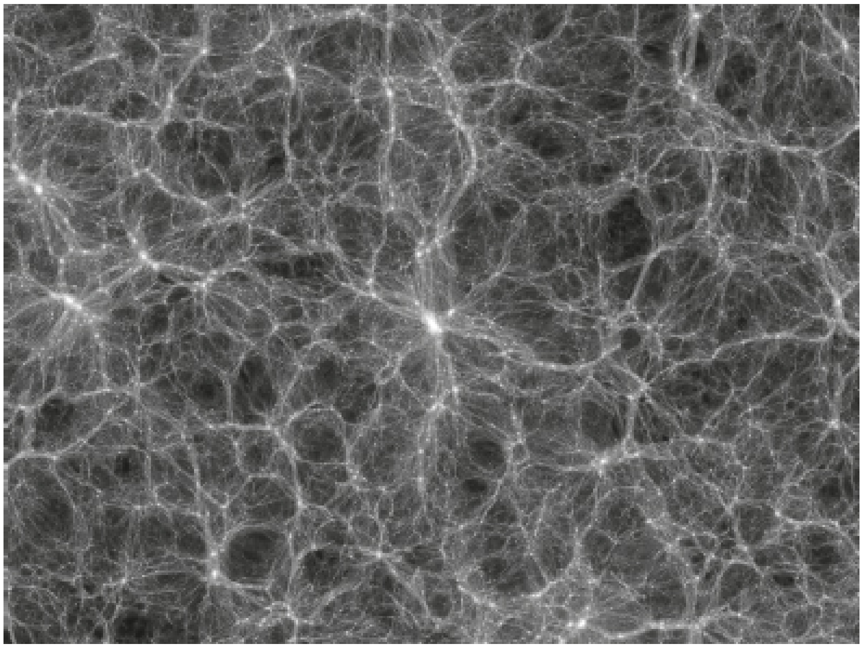

Figure 14.6. The Millennium Simulation giving a large-scale (bigger than galaxy clusters) perspective on the distribution of dark matter in the universe. Note the voids!

Beyond that, we know very little about dark matter. It remains a great mystery. Does it interact with the standard model at all? Is it just one type of particle, or is it a whole dark sector with many particles? And is dark matter related to dark energy?

Science Is About Questions, Not Answers

When I was a high school student, neutrinos were still considered a potential candidate for dark matter. They're very difficult to observe, to the point of needing highly specialized detectors and experiments. There are ways in which they are invisible to us—they don't interact with electromagnetic radiation at all. Are they dark matter? No: Neutrinos are the edge of visible matter.[*] That's not enough for them to be dark matter, though. It eventually turned out they weren't massive enough to explain all the missing matter. Eventually we learned that neutrinos have some modicum of mass, just not very much.

Typically, we physicists refer to dark matter as "BSM"—beyond standard-model physics. For now, that's true. But will it always be so? We may eventually work out how dark matter interacts with the standard model, leading to a reorganization, with what we now call dark matter falling into the category of what we currently name as visible matter. Physicists working on dark matter have used "visibility" to mean what can be seen not only via interactions with light but also more broadly through interactions with the standard model—so neutrinos are visible matter, though "seeing" them through electromagnetic interactions is hard. But remember, the term "dark matter" is a container for something that doesn't have detectable interactions with the standard model as we now understand it. We use it, linguistically and scientifically, to hold space for our ignorance—it is the boundary of the matter types known to humanity. And this, in principle, is where theoretical physicists shine: It is our job to craft stories that are plausible explanations of the unknown.

Indeed, there are many proposed theories to explain dark matter. There are a few major categories and paradigms. First, we have to distinguish between dark-matter particle candidates that are *hot* dark matter (fast-moving) and *cold* dark matter (slow-moving). These days, all available data indicate that cold dark matter (CDM) is a better fit than something where the particle components move fast. That narrows it down, but not a ton—we still have hundreds of different dark-matter models to wade through. One popular proposal is that CDM is composed of weakly interacting massive particles (WIMPs). This is a highly descriptive name for a model in which dark matter does have standard-model interactions via the weak nuclear force.

WIMPs are more a framework than a specific proposal. With a specific model, we can write down a quantum field theory to describe it. Such a theory would specify the mass of the particle, and its properties such as its electromagnetic charge, its spin, and so on. There are a lot of models that fall in the WIMP category—for example, most particles that are proposed by the supersymmetric extension of the standard model (SUSY), which suggests that every boson has a fermionic partner known as a superpartner, and vice versa. Importantly, these are not antimatter particles but rather a completely new category of particle. We would expect to see SUSY in high-energy collisions between particles slammed against each other at high speeds at the Large Hadron Collider of the European Organization for Nuclear Research (known by its French acronym CERN, which stands for Conseil Européen pour la Recherche Nucléaire). Unfortunately, all experimental searches for

SUSY have come up short. But that doesn't mean that it's wrong: There's no cosmic rule that says SUSY has to exist at the energies where we first looked for it.

This is a political problem as much as a scientific problem. From our earliest moments of consciousness, we are socialized to believe that science is supposed to produce results, not questions. Scientific funding is organized around the idea that a good experiment is one that "works," and that means it finds new ideas and new information. But this is a very skewed understanding of what good science should be. Null results, where we find nothing, are just as important as experiments where we find something new, because null results can tell us where something isn't. Something I'd like the people who hold the purse strings—the general public and its representatives—to understand is that when we look for dark matter of a certain mass and standard-model interaction and don't see it, this helps us know what dark matter can't be. Not finding evidence for the simplest supersymmetric extension of the particle physics we know—the minimally supersymmetric standard model (MSSM)—is important evidence. For what? We don't necessarily know, but this particular null result taught us that there are no SUSY particles that fit the MSSM at the scales where we looked for it. Many of us still remain interested in the possibility that SUSY is out there, though.

One example of a problem many of us hope that SUSY may solve is the electroweak hierarchy problem. Earlier, I pointed out that the strong nuclear force is stronger than electromagnetism, the weak nuclear force, and gravity —in that order. The jumps between the strong force, electromagnetism, and the weak force are all within a few orders of magnitude of each other. But the difference between the strength of the weak nuclear force and gravity is, by comparison, enormous: a 10^{24} difference in strength. This is often referred to as the electroweak hierarchy problem. With a huge difference in strength between these forces, we might expect that there is a mechanism that causes it—the problem is that there is no apparent mechanism, although of course the problem may be seeing things in terms of hierarchies in the first place.

Another way of thinking about the hierarchy problem is to ask the question of why the masses of the W boson, Z boson, and Higgs boson are so relatively small. It's often underappreciated that one reason observing the

Higgs for the first time in 2012 was of great significance was not just because of the detection of a new elementary particle but also the discovery of the mass of the Higgs. The mass of the Higgs turned out to be on the lighter side compared to the Planck scale—the highest energy scale (and shortest distance scale) in the universe.[*] And the fact that the Higgs, along with all particles that gain mass from it, seem to steer clear of the Planck scale—and are in fact well below it—is also an expression of the hierarchy problem. The hope had long been that SUSY would resolve this problem by giving the field theory new elements that act as a mechanism for adjusting the Higgs mass down from the Planck scale. The possibility that the new particles it introduces might also solve the dark-matter problem is a nice bonus.

Dark-matter theory is full of ideas like this—ideas that are essentially a fringe benefit of existing field theory models meant to solve other particle-physics problems. I have spent most of my post-PhD career in the bubble of one such model—the axion.[†] The axion, like all the SUSY particles, is a hypothetical idea driven by a desire to solve open problems in particle physics. In this case, Roberto Peccei and Helen Quinn in the late 1970s were hoping to address a serious (and as of this book's publication, unresolved) issue with the standard model—namely, that it predicts the neutron has a sense of charge that we have never observed, despite intensive searches. The Peccei– Quinn mechanism resolves this problem by introducing a new field that helps the charge-adding part of the standard model disappear.

One consequence of this field is a new particle, now popularly known as the quantum chromodynamics or QCD axion (thanks to Frank Wilczek, whose choice of name beat out Steve Weinberg's [in my opinion] superior "Higglet"). The axion has exactly the right properties to be a good dark-matter candidate. The field of axion physics has since blossomed into a flourishing research area, especially in the wake of SUSY's experimental elusiveness. Even within the model, there is still a lot of theoretical flexibility, and experiment is only very slowly setting boundaries around what is possible and what isn't through a series of null results.

When I say "the axion," I could mean a specific type of model or a class of models. But let's say that I mean specifically the most vanilla model, the QCD axion. To explore even this one idea, there are many choices to be made, and the cosmological timeline is an important factor. When did axions come into existence: before or after the inflationary period? You would get different dark matter and thus structure formation scenarios in which axions form before inflation, compared to those in which axions form after inflation. If the axion field turns on during inflation—giving rise to axion particles—then the region of axions with the same properties is rapidly stretched out along with the rest of space-time. But if they form afterward, the axion field isn't uniform, because there's no inflation to make it so, and as a result its properties vary across the universe. This potentially creates a variety show of interesting effects, which are fun to think about as a theorist—b ut also not a guarantee, of course, that the universe actually *is* that way.

For the last seven years, my research group has been systematically studying how modifications to the quantum field theoretic properties of the axion, including scenarios with multiple types of axion, might change the evolutionary behavior of dark-matter halos.[3] We have no idea if the axion is out there, but it may be that our work will help rule out the possibility that it is. This null result would be an important victory. Knowing that the axion doesn't exist would return us to the drawing board with the question of why the standard model predicts that the neutron will have a distribution of charge in it that we've never detected.

I get asked with some frequency about the possibility that we might not work out the dark-matter problem, at least not in my lifetime. This is not just a random awkward question that essentially is about whether I am wasting my life (I'm not, but thanks for asking). It is also a question about whether taxpayers should keep paying for me to do this work. In some sense, this entire book is my answer to this question: Everyone who is touched by my words has felt the impact of the public investment in science, from my time as a Pell grantee college student, to my time as a National Science Foundation Graduate Research Fellow, then NASA Postdoctoral Program Fellow, and now federally funded researcher and professor at a public university. A scientist is the end point of a collective commitment to knowledge gathering.

Dark matter may feel like impossible nonsense to us, but it's out there, and it continues to inspire. You picked up this book (and read this far, thank you!). You may also have read Govert Schilling's *The Elephant in the Universe* —or another book about dark matter. But also, I think it's good to work on ideas that stretch our imaginations. I'm *not* Alice in Wonderland, but it is my job to imagine which Wonderland might coincide with our reality. Soon after Alice went through the looking glass, she found a book on the table that looked like it was in a foreign language. Eventually she realized she had to hold it up to the mirror to read it. What she saw was a poem, "Jabberwocky," that opens, "'Twas brillig, and the slithy toves / Did gyre and gimble in the wabe."[4] It's a poem that doesn't make any sense, composed primarily with words that Lewis Carroll made up. Even so, for over a century, children have grown up reading and loving it. *Alice* is so embedded in our culture that even *Star Trek: Discovery* used the story as a reference for its own narrative about the strangeness of journeys through space. The way our work becomes part of people's cultural world is enough for me to know that none of this is a waste of our time or money. Over and over again, we find meaning—poetry, prose, music, art—in the cosmos, even the parts that we may never see.

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* For a perspective on visible matter in galaxies, from the hypothetical point of view of a sentient galaxy, I highly encourage readers to pick up Moiya McTier's *The Milky Way: An Autobiography*.

Go to note reference *

* In 1935, Japanese physicist Hideki Yukawa wondered whether nuclear forces could likewise be quantized, leading to new particles. Using this idea, Yukawa predicted the existence of a particle that was eventually observed in 1950: the pion.

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† 10^{38} means a one with 38 zeros after it—a much bigger number than a trillion, which is 10^{12}, or a million, which is 10^6.

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* Interestingly, despite their fundamental functional differences, both the strong and weak nuclear forces can be approximately described by a similar type of field, known as a Yang–Mills field after Chinese theoretical physicist Chen Ning Yang and his American collaborator, Robert Mills.

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* For more on their work, see: Gaillard, *A Singularly Unfeminine Profession,* and Ahn, "Re-Remembering Benjamin Whisoh Lee, Promoter of Gauge Theories." Benjamin Lee survived the Korean War and came to the United States as a transfer student before going on to become the first head of theory at Fermilab. There he hired a diverse group that included Gaillard as well as the first Black woman to earn a PhD in high-energy physics and have a staff position as a particle theorist, the second Black woman to ever earn a PhD in any area of physics, Shirley Ann Jackson.

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* Seyda Ipek gives a nice overview of this question, which is often referred to as "baryogenesis," at the start of her talk for the Australian Institute of Physics, "Why Are We Here? Matter-Antimatter

Asymmetry of the Universe," which can be found on YouTube at www.youtube.com/watch?v=EBKaPITN50w.

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* Lee and Yang won the Nobel Prize in 1957 for their proposal. Chien-Shiung Wu was excluded by the Nobel committee from the prize, even though her experiment was the one that verified Lee and Yang's theory. The argument for why this is reasonable is because she declined to put her name on the paper for the theory. But of course, the Nobel committee certainly could have been aware that her experiment was a major contribution, since Yang and Lee cited it. She later received other prizes recognizing her contribution but never received a Nobel. To learn more about her contributions, look back at chapter 9, "TRAP Phenomenology," read on to chapter 17, "Cosmic Energy," and also read "Chien-Shiung Wu's Trailblazing Experiments in Particle Physics" by Chon-Fai Kam, Cheng-Ning Zhang, and Da Hsuan Feng in the December 2024 issue of *Physics Today*. If you like podcasts, check out the two-part series by NPR's *Short Wave* about Chien-Shiung Wu, "The Queen of Nuclear Physics."

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* Thanks to the affecting title of Nicole Chung's powerful memoir *All You Can Ever Know,* I often think about dark matter as all of the universe that we may never see.

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* I encourage you to do a search engine image search using the phrase "Priya Natarajan dark matter galaxy cluster" so you can see some examples of the dark-matter presence overlaid on galaxy cluster images from the Hubble Space Telescope.

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* Although, actually, there was a 2023 paper that claimed maybe there is a scenario where neutrinos do have brief moments of electromagnetic interactions. So maybe we just don't understand them. By this point in the book, you know that's a pretty normal situation for physicists!

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* The way to think about the Planck scale is that this is the arena where the effects of quantum mechanics and gravity simultaneously become important: the quantum gravity realm, which I'll discuss in chapter 16.

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† I'd like to thank Brian Shuve for pointing out that also, if dark matter really is axions, then we actually do live in an axion dark-matter bubble. My metaphor might actually turn out to be literal.

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CHAPTER FIFTEEN

THE ULTIMATE TOOL FOR LAYING EDGES

In which we go down to the edge of a black hole

James James
Morrison Morrison
Weatherby George Dupree
Took great
Care of his Mother
Though he was only three.
James James
Said to his Mother,
"Mother," he said, said he:
"You must never go down to the end of the town, if
you don't go down with me."

—A. A. Milne, "Disobedience"[1]

In these opening lines of A. A. Milne's poem "Disobedience" we meet James James Morrison Morrison Weatherby George Dupree, a toddler who is somehow responsible for his mother. For unknown reasons, she's not supposed to go to the edge of town without him. You can guess what eventually happens: "SHE TRIED TO GET DOWN TO THE END OF / THE TOWN—FORTY SHILLINGS REWARD!" By the poem's end, his mother hasn't been found, but James James affirms for the reader that she really should have listened to him: for whatever reason, the edge of town is dangerous.

In context of the message about not wandering off, it's perhaps not surprising that my dad read this poem to me when I was a toddler—a lot. So many times, in fact, that I memorized the poem and learned to read sentences by matching the words I knew with the words on the page. Forty years later, I can still recite the entire poem, which is definitely meant to be read aloud. And while the poem's central conceit is a funny inversion where a child parents his parent instead of the opposite, it also offers a neat allegory for what happens if you don't listen to your dorky physicist friend about going to the edge of a black hole. It's a one-way ticket. You can cross over the event horizon, but you won't be coming back.

Black holes are the edge of space-time as we understand it. They are, after all, "the singularity that swallows all, / everything, even light," as Matt W. Miller puts it in his poem "The Adorned Fathomless Dark Creation."[2] Black holes swallow everything that go past their event horizons. That's maybe the one thing everyone knows about them. If nothing else in the universe has a well-defined edge, surely black holes do, right? But black holes are fascinating in a way that focusing on the event horizon does not help us understand. Black holes are not just space-time freaks; they are also a nexus. Though the black hole is a point of no return, for the theoretical physicist, they are a possible gateway to the theory of our dreams: a theory that unifies quantum mechanics and general relativity.

A Fake Catastrophe and a Real Catastrophe

The best laid edge in the universe is a black hole, a region of space- time where gravity is incredibly strong—so powerful that light cannot escape. All relativistic effects near a black hole are extreme. You might recall that in chapter 3 I described gravitational time dilation using a fictional planet from the film *Interstellar*. Miller's Planet is near a black hole, but in a stable orbit where it will not eventually cross the event horizon. The time distortions near a black hole are extreme, to the point where someone close to the black hole can experience an hour passing while someone a much greater distance away will experience years.

Black holes begin in catastrophe, conceptually. It begins with zero. We think of zero as the number that symbolizes the absence of anything: Rather than quantifying how much stuff there is, zero quantifies how much stuff there *isn't*. This seems like a natural concept, since we live in a world where sometimes there is nothing of the thing we are quantifying, like the amount of money in the bank accounts of first-year graduate students at the start of the academic year who must wait a whole month to be paid. But zero is a concept that humans had to arrive at, not something that was implanted in our brains from the start. Records show that Egyptians had one of the earliest concepts of zero, around 1770 BCE. The Mayan concept of zero, which dates to at least 36 BCE, was probably inherited from the Olmecs, who were temporal (though geographically separated) contemporaries of those early Egyptians. The Greeks of the same era did not have their own idea of zero but eventually adopted the Babylonian one. The idea of a symbol that represented nothing was a conceptual step that clearly had some cultural embedding. Zero was not a given.

I was fourteen when I guessed that singularities are linked to an equation where a number is divided by zero. In my calculus class, I had learned that dividing a number by zero caused equations to "go to infinity," as we say colloquially. Around that time, I spent a lot of bus rides back and forth to school trying to visualize four dimensions (not possible!). During one of these moments of reverie, I wondered if a black-hole singularity was the physical version of trying to divide a number by zero. When I excitedly asked my math teacher, Mr. Buckner, if he thought I was onto something, he said yes. It was a lucky guess—I was working from the assumption that I understood zero, when in fact all I really knew was that I had been taught that dividing any number by zero is "illegal" in math.[*]

In some ways, it really is this simple. The mystery that surrounds black holes is genuinely matched by a relative mathematical simplicity. It is one of the easiest solutions to Einstein's equation; no computational complexity necessary. Remember that Einstein's equation is a differential equation that allows us to calculate a formula—the metric—which tells us how distance is measured in space-time, in essence giving us information about its shape. The most important factor in solving this equation, as you learned in chapter 5, "Beyond a Cosmic Boundary," is the boundary condition, which gives information about the specific problem we are trying to solve and places bounds on how the equations should be solved. The simplest black- hole solution—the one developed by Karl Schwarzschild (as described in chapter 3)—emerges from making very simple assumptions, a boundary condition of spherical symmetry and no change over time. This means that space-time is both unchanging and spherically symmetric, and even if we rotated it, the properties of the system would be the same.

No one knew ahead of time that these assumptions would yield this outcome. This result, known as the Schwarzschild solution, is useful for any system where there is spherical symmetry. So we can use it to model the space-time around stars. But in those scenarios, we are dealing with a material object, while the Schwarzschild metric solution does not require the presence of an object at all. The Schwarzschild solution is a vacuum solution, in the general relativistic sense, which is to say that it assumes the space-time is empty. This invites one of the first interpretations of the black hole as not an object but rather a region in space-time.

The key marker of that region is the event horizon, which can be thought of as a location in space-time beyond which everything is trapped—nothing, not even light, can travel fast enough to escape the gravitational pull of the black hole. The event horizon appears to be a very hard edge to space-time—a region of space that is cordoned off by a spherical boundary. The metaphor of a hole for this location invites us to understand it as a ledge, a place where you might fall in; thus the material nature of the black hole is first conceived of as a point of no return.

To understand the point of no return is to reckon with how we create maps of space-time. Ultimately, the thing that characterizes the nature of any region of space-time is its metric, which captures information about how distances in space-time are measured. In other words, the metric defines the concept of length for the space- time. To actually describe the metric, we need to use a coordinate system, a concept first introduced in chapter 2. A coordinate system is a systematic way of naming each location in space-time. In the case of the simplest black hole, because it is spherically symmetric, the easiest thing to do is to start with a coordinate system that is natural for a sphere—a curved, not Cartesian system. Of course, there is also a time coordinate that accounts for how time ticks in this space-time.

Before we get into how time ticks, let's consider what happens with the distance coordinate. The equation we get has two places where division by zero arises. The first is at the locations where the distance is equal to roughly twice the mass parameter—this is just how it works out mathematically.[*] So now we can imagine a region that has the shape of a sphere with a radius (distance from the center) that is two times the mass parameter—this is the famed event horizon. The second is when we set the distance coordinate equal to zero—this is the famed singularity. And when we are confronted with division by zero, you already know it's gonna be a problem! The question is: What kind of problem?

In the case of the Schwarzschild solution, the first division by zero that we encounter as we move toward the center of the system is actually something of a false alarm—it is not a real singularity but instead the place where the simplest way to write the equations is not up to the task of fully describing the system. This is what we call a coordinate singularity, one that can be resolved if we introduce a new mapping—a new set of coordinates to mark events in our space- time—that will get us beyond the simpler formula that we started with.

That doesn't mean the spherical surface where the first catastrophe happens isn't special. It is. A good choice of coordinates to map out the area reveals this point as one where the properties of space-time shift dramatically. This is the event horizon. Inside, the light-like paths—the possible trajectories of photons—can no longer point in just any direction. They all point away from the spherical surface, which means they all point away from the event horizon toward the interior. None of them point in a direction that would lead to one traveling to or across the surface. In other words, the light-like paths are all trapped inside. Because the speed of light is the fastest anything can go, light-like pathways establish the boundary for all possible causal pathways—if light must go toward the center, so too must any other particle or material phenomenon. If light can't go back toward the surface or past it, neither can anything else that has crossed that line; instead, everything inevitably moves forward, just like the arrow of time. Any particle that crosses the line has crossed the event horizon. The fake division by zero is a point of no return, a true edge of space-time.

Every trajectory inside the event horizon, which marks the edge and beginning of the black hole, leads inevitably to another division by zero. And this time, it's a real one. We can show that at the very center of the sphere is a singularity, one that won't go away no matter how we map out the system.

We can even show that it's impossible to come up with coordinates that will fix this problem, because the mathematical object that measures curvature at that point goes to infinity. This is the first singularity that general relativity ever encountered, and it is just as mysterious as the so-called Big Bang.

Does this mean that the curvature of space-time is infinite at the center of a black hole? That's one interpretation, although it might not be a very good one, since "infinite curvature" is a bit of a nonsensical notion. Instead, we are forced to consider the possibility that rather than space-time itself breaking down, our theory to describe its nature has failed us.

A Classical Black Hole, in Theory

You might wonder what it would be like to cross the event horizon.[*] But would you even know? And what would your colleagues see if you went for a space walk across the event horizon? There isn't a signpost marking the event horizon: edge of town. don't go past this point. Except for, of course, the extreme tidal effects of being near an object like a black hole. For context, a black hole with the mass of the Earth would be only about 1 centimeter across; a black hole with the mass of our sun would fit into a small section of downtown Los Angeles. Getting close to even the "smallest" black hole would be quite dangerous.

As a result of the extreme gravitational conditions, the distortions to space-time would of course be quite noticeable. There is no place in the universe where space-time is more distorted than at the edge and interior of a black hole. As I described in chapter 11, where there are strong space-time distortions, we can expect space-time to act like a funhouse mirror like the one in Jordan Peele's film *Us*. If someone were to approach a black hole, they would increasingly experience the most intense gravitational lensing effects to be found anywhere in the universe. Things would look oddly curved, and light sources would appear brighter and brighter. These distortions would be centered on the black hole, a region where there is no light. That blank region would start to seem bigger and bigger until eventually it took up the observer's entire sky.

At a distance of almost two times the size of the event horizon, the observer would begin to see no light, because the gravitational effect of the black hole would cause the light that doesn't fall into the black hole to bend away from the event horizon. Eventually, as the observer crossed the event horizon, all they would see is a tiny dot of light, which would change colors as the gravitational redshift changes the wavelength that arrives to their sensors. (This is in a scenario in which there aren't light sources falling into the black hole along with the observer; if there were, then their perspective could potentially be dominated by the observable effects of those light sources being pulled apart.)

In reality, however, any human observer or spaceship would be torn apart well before they could cross the event horizon. This would be a bottom-to-top process: The part closer to the black hole would be more stretched out than the part farther away, due to the same kind of tidal effects that cause ocean tides on Earth. In the case of our oceans, the moon's gravitational pull on the Earth causes the oceans to bulge out a little, leading to tides both on the side of the Earth closest to the moon and on the side in exactly the opposite direction. Any object falling into a black hole experiences this same kind of distortion—the part nearest to the black hole will experience much stronger forces than the other side, with consequences for the structural integrity of the entire object.

How would all of this look to someone watching their friend make a one-way trip toward the singularity? Due to gravitational time dilation, it would seem like their friend keeps slowing down, although the person entering the black hole would experience their time as flowing normally. At the event horizon, where time dilation is at its most extreme, from the perspective of the observer, the friend would freeze but never actually disappear beyond the event horizon. Depending on how you look at it, this is either heartening or depressing: You would never see a friend disappear into a black hole, but you'd also never have the satisfaction of watching them complete their planned mission.

But Also: Quantum Field Theory in Curved Space-Time

As you've learned, quantum mechanics will fuck you up, and this still applies even if the "you" is a black hole. Everything I've said up until this point assumes that the black hole is classical—it is only described by general relativity; there are no quantum mechanics taken into account at all. But this is an idealization that no one should expect to be borne out in reality, since we know that reality itself is quantum- mechanical at subatomic levels.

You might argue that it's sensible to ignore quantum mechanics in this scenario, because black holes exist well above the scales where we should have to concern ourselves with quantum mechanics. After all, a centimeter is giant compared to subatomic particle length scales. And in defense of anyone who wants to argue that point, I'll share the second sentence in a review of the quantum mechanics of black holes that my friend, physicist Daniel Harlow, published in 2023: "It must be stated at the outset that this is not an experimental subject, and it does not seem likely to become one in the near future."[*] Harlow sees that this might make people question why anyone should do what he does, and I think his response a few paragraphs later is the right one:

> Given all these obstacles, why study the quantum mechanics of black holes? There are various answers which have been given, but perhaps the most compelling is the following: we know that black holes exist, and we know that our world is quantum mechanical, and so it must be that nature finds some way to combine them.

Part of what's incredible about understanding some of the fundamental precepts that seem to govern our universe is that we are then invited to ask the question over and over again about what those precepts mean for any given physical scenario that might capture our attention. Black holes, even if we were unable to directly study them (we *do* directly study them!), are fascinating because they are an extreme reflection of our universe's possibilities. Even without quantum mechanics.

But *with* quantum mechanics? It turns out that black holes open the door to understanding problems that initially seem to have nothing to do with them. To think about the quantum mechanics of black holes is to begin to explore quantum field theory in the vicinity of black holes. And quite surprisingly, understanding quantum field theory in the vicinity of black holes not only provides a possible portal to a complete theory of quantized gravity; it also reveals that black holes might actually not be perfect absorbers of information. A quantum-mechanical black hole is a different beast from a purely relativistic one, because a quantum field theory in a curved space- time is a different beast from the quantum field theory in the flat space developed by particle physicists.

One of the things that happens with quantum field theory, as we learned, is that particles can be created and destroyed in the vacuum. But *whose* vacuum? An accelerating observer will not necessarily see the same amount of particle production in the vacuum as another observer. That's right—two observers will not necessarily agree on how many particles are present! This is what happens when we put general relativity into conversation with quantum field theory. An accelerating observer in supposedly empty space will experience the space-time as having particles and a sense of temperature (what is known as a thermal bath): the Fulling–Davies–Unruh effect. Motion determines our sensibilities about whether a quantum field is excited or not. Motion also determines an observer's sensibility about what temperature should be assigned to a region of space.

Because acceleration is equivalent to a gravitational field, we see these kinds of particle production effects anywhere that general relativity is at work. In the case of a black hole, the Fulling–Davies–Unruh effect implies that there is a temperature associated with the region of space-time that constitutes the black hole. Jacob Bekenstein first proposed this link in 1972, suggesting that because black holes have a sense of temperature, they also have a sense of entropy, a concept you might remember from chapter 10. Not long after Bekenstein made his proposal, Stephen Hawking showed how to calculate the equation linking black-hole entropy and the size of the black-hole region that Bekenstein had first proposed. He showed that this was connected to the black hole having its own sense of a thermal bath. In other words, black holes had a radiation associated with them, known today as Hawking radiation.[*] Black holes aren't pure absorbers—there is particle production associated with them.

That could feel like a shock to anyone who has only heard about black holes in the classical sense. They are supposed to be the ultimate absorbers; the place where all things go, never to emerge again; the ultimate shredder where information can be permanently disappeared. Except that black holes are in fact *not* a place where information can permanently disappear.

Carrying out the calculations to their logical conclusion, the existence of Hawking radiation implies that, given enough time, a black hole can evaporate. And while it's in the process of evaporating, black holes actually get hotter. This is very weird and very cool (though not literally, obviously).

And that's not even the end of it: Quantum field theoretic analyses of black holes suggest that black holes do not "remember" how they were born, meaning that the radiation they emit does not contain meaningful information about the black hole's past. So even though black holes are putting out information, that information offers no insight into the black hole's initial conditions. This violates all of our sensibilities about determinism in physics, even in quantum mechanics. Even in traditional low-speed, low-energy quantum mechanics with no gravity, the wave function's time evolution can be determined forward in time and can therefore be reverse-engineered backward in time. But now we know that the state of a black hole cannot be run backward, even in the scenario where the black hole totally evaporates and all of its information is released into the universe. You have just met what we call the black-hole information paradox.

And this is what it means to think about quantum field theory in curved space-time, a calculational framework that has implications in cosmology (since space-time is expanding) as well as black-hole physics. Importantly, quantum field theory in curved space-time is not the same thing as a quantized theory of general relativity, or a quantized theory of gravity. In quantum field theory in curved space-time, there is no quantization of gravity, which remains a classical effect. The question of how to define a quantum theory of gravity or a quantum field theory with gravitational particles (known as gravitons)—quantum gravity for short—remains the biggest challenge in the universe of physics, besides convincing self-interested politicians that they should fund basic science.

A Black Hole in Practice

The space-time catastrophe caused by zeros ruining things—the black hole—is a curious object because it resists full classification. There are two conceptual categories of black holes: the theorized ones that initially arose in general relativity, and the astrophysical phenomena that we have actually observed. As Harlow describes in his review, there are not many experimental prospects ahead when it comes to this work. Hawking radiation is observable in theory, but in practice, it's not possible—it would produce such a weak signal that no telescope would be able to distinguish between observations of Hawking radiation from a black hole and radiation from other sources. The most obvious black holes in our universe are surrounded by a lot of other radiation-emitting stuff.

Even so, we have never been closer to merging theorized and astrophysical black holes, since the Laser Interferometer Gravitational- Wave Observatory (LIGO)/Virgo Collaboration detected gravitational waves from a black-hole binary merger in 2017 and the Event Horizon Telescope published the first images of the region around a black hole's event horizon in 2019. The latter was particularly significant because a black hole's event horizon has captured the public's imagination like few other physical concepts.

Until these discoveries, astrophysical black holes was an area of research that didn't require us to understand anything but the simplest general relativistic calculations. Supermassive black holes—between a million and a billion times more massive than the sun—are thought to be at the center of all galaxies, including our own. Each of these is surrounded by stuff that it has pulled into orbit, called an accretion disk; due to the dynamics of the system, much of it is quite hot, and therefore also quite bright. There are particles moving at relativistic speeds, causing them to radiate light we can observe. It is expected that these accretion disks and the light they radiate play a role in galactic star formation and the evolution of galaxies themselves. In other words, in practice, black holes are engines of creation.

Some galaxies, known as active galactic nuclei (AGN), have such massive black holes that their especially bright accretion disks outshine the rest of the galaxy. AGN radiate brightly across the electromagnetic spectrum, including in visible wavelengths. They have very distinct observable features, which scientists work hard to understand. For example, in her dissertation work, Jedidah Isler used several years' worth of data to understand jets of particles that are emitted by certain types of AGN.[*] These jets are a great mystery, as they fly out from the center of the galaxy, but we don't fully understand what sets them off. Isler's work has helped us narrow down the possible emission mechanisms. AGN are especially powerful radiators of X-rays and gamma rays, the highest-energy photons. This kind of light is mostly absorbed by Earth's atmosphere, so we are only able to observe them from space-based facilities. Our optical, ultraviolet, and infrared space observatories like the Hubble Space Telescope and its successor JWST (which I like to call the Just Wonderful Space Telescope) tend to get all the attention.

But there are also telescopes that look at the high-energy sky—the sky from the point of view of short-wavelength, high-energy photons like gamma rays and X-rays. The Fermi Gamma-Ray Space Telescope focuses on surveys of AGN and searches for evidence of dark matter. Isler's research required cross-wavelength analyses and made use of data from Fermi. Meanwhile, the Chandra X-ray Observatory, the only NASA great observatory ever named for a person of color, has been an important workhorse for people doing research on not only black holes but also supernovae, galaxy structure, and a host of other astrophysical phenomena for over twenty-five years.[*]

Black holes that have masses more like stars than supermassive black holes are a hot topic of research these days, thanks to the detection of gravitational waves. Until recently, we could only study astrophysical black holes using light. Since detecting gravitational waves, we have seen more stellar-mass black holes than expected, which could be explained by a population of primordial black holes that formed in the early universe in the aftermath of inflation. This has revived the possibility that there might be enough of them to explain dark matter. Arguably, this is the only dark-matter candidate that is genuinely a dark absorber of light.

In fact, a funny thing happened on the way to writing about dark matter for chapter 14. I started wondering how black holes fit into the way science communicators like me typically talk to the public about the cosmic matter-energy pie chart. We usually show people something like Figure 14.1. On that chart, where do black holes belong? This, it turns out, is not a straightforward question. Black holes aren't exactly matter or energy—we don't really know what's beyond the event horizon. Maybe a mix of dark energy, dark matter, and visible matter. Or maybe black holes are dark matter themselves!

As the 2020s unfold, we are in an era of what Dr. Delilah Gates refers to in her dissertation as “the era of precision black hole imaging.”[*] Using the circumference of the Earth as the aperture for a radio telescope, the Event Horizon Telescope collaboration has for the first time delivered images of the event horizons of two supermassive black holes. The first, the black hole at the center of galaxy Messier 87 (M87), was revealed in April 2019. In 2022, humanity was able to look at the edge of our own galaxy’s interior, the event horizon of Sagittarius A*—aka Sgr A* (pronounced “SADGE-ay-star”)—the black hole at the center of the Milky Way. The images that we received, which you can see in Figure 15.1, exemplify the strong gravitational lensing I described earlier—and they look just like the computer simulations scientists had done for decades, based on theory alone.

Now, for the first time in the century since humans first started studying black holes, we are at a point where fundamental physical ideas about black holes are beginning to be tested with real data. As Daniel Harlow pointed out, we may not get to the point of fully testing our ideas, but we are increasingly able to make realistic statements about what black holes are like and how they manifest in our universe. They are important clues, including in our search for unity between gravity and quantum mechanics.

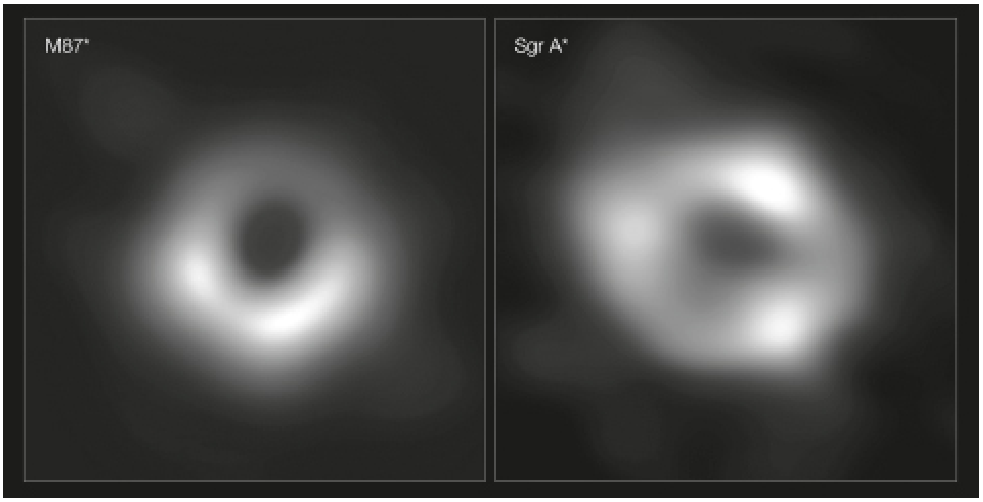

Figure 15.1. These panels show the first two images ever taken of black-hole event horizons. On the left is M87*, the supermassive black hole at the center of the galaxy M87, which is 55 million light-years away. On the right is Sagittarius A* (Sgr A*), the black hole at the center of our own galaxy, the Milky Way. The two images show the black holes as they would appear in the sky, with their bright rings appearing to be roughly the same size, despite M87* being

around a thousand times larger than Sgr A*. The images were captured by the Event Horizon Telescope (EHT), a global network of radio telescopes, and can be seen in color online.

Increasingly, black holes also play a powerful conceptual role in human culture. They are portrayed in film and television, and they have made their way into books. Meanwhile, Evelynn Hammonds, historian of science, African American studies theorist, and physicist, has made the case that black holes can help researchers expand the metaphors they use to interpret and analyze Black lesbian experiences.[3] Rather than disappearing information, black holes seem to be both energetic and quite generative—not just for space-time itself, but also for us on Earth.

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* Time for a confession: I am a mathematician at heart. Patterns in numbers are my first love. My second is the idea that the physical world can be described using elaborate mathematical patterns. Why is the universe like that? That's the question that still makes my heart squeeze the way my extremely serious teen crush on Christy Turlington once did. Math seems to be able to do it all, even if we can't do all the math.

Go to note reference *

* This is exactly correct if we assume the gravitational constant and speed of light are set to 1, something theorists do a lot to simplify equations and gain physical insight into the system. This sounds like we are breaking math, but we still have to keep track of what's an ox and what's a horse, as the Mohists might say. This is something that we are taught to do during our PhD training.

Go to note reference *

* I found Ethan Siegel's writing about this to be illuminating, so if you read this section and enjoy it, consider checking out his detailed explanation with some nice visuals, which can be found at: www.forbes.com/sites/startswithabang/2018/01/19/what-would-you-see-as-you-fell-into-a-black-hole.

Go to note reference *

* You can read "Black Holes in Quantum Gravity" yourself. It is available for free to anyone with internet access on the arXiv, a website I encourage you to explore: http://arxiv.org/abs/2304.10367.

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* To learn more about this, of course I recommend Hawking's classic *A Brief History of Time*. It provides a nice discussion for general audiences about the details of Hawking radiation from his own perspective.

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* Isler, "In Like a Lamb, Out Like a Lion." Dr. Isler is an incredibly accomplished scientist. She is the first African American woman to earn a PhD in astrophysics at Yale University. She went on to hold a position at the Harvard | Smithsonian Center for Astrophysics and to be faculty at Dartmouth College before taking a role in the White House Office of Science and Technology Policy, where she led the Science and Society Division during the Biden administration. Dr. Isler was also one of the youngest

appointees to the 2020 Astronomy Decadal, which determined the astronomy community's direction for the 2020s and beyond. I have been lucky to be in the same generation of scientists as her.

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* Chandra was named for Tamil physicist Subrahmanyan Chandrasekhar, who played a key role in developing the theory of how black holes form in practice. While sailing from India to England to begin a graduate program, Chandra, as he was nicknamed, figured out the maximum mass a star could have before it would collapse into a black hole. This is called the Chandrasekhar limit, and it is a guiding number in research on stellar-mass black holes and stellar remnants like white dwarfs and neutron stars (what remain in the aftermath of a supernova).

Go to note reference *

* Gates, "Observational Electromagnetic Signatures of Spinning Black Holes," 3. Dr. Gates is a rising star in the world of astrophysics and one of the first Black women to earn a PhD in theoretical astrophysics—the first, I believe, from Harvard.

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CHAPTER SIXTEEN

U.N.I.T.Y.

In which we pull our quantum gravity edges together

Just a few pages into his world-famous book *A Brief History of Time,* Stephen Hawking boldly declares, "The eventual goal of science is to provide a single theory that describes the whole universe."[1] Imagine the possibilities: A theory of everything, a model that tells us exactly what everything is doing. As a child, I naïvely interpreted this to mean a theory that would explain *why* everything is the way that it is—and that we would have the answers to life's most difficult questions, such as how to build a society where injustice did not occur. It was my sincerest hope that I could contribute to our understanding of how to do this by uncovering the universe's innermost workings.

There is a kind of irony that I ever had the impression it could work this way, since our current understanding of quantum mechanics makes abundantly clear that indeterminacy is foundational to the universe. There is no true hope for a deterministic or predictive model of the universe. There are things we can know for certain, and other things that will always be uncertain and a matter of quantum randomness. This is, on some level, easy for me to accept. I can accept that I won't know a priori whether any given electron is spin-up or spin-down and can only guess based on population statistics. I can accept that I will never be able to simultaneously calculate the exact location and momentum of a particle, because there will always be a level of detail that is fundamentally uncertain. One reason this is easy to accept is because it is below the scale of my everyday life. I don't worry about individual atoms when I get in my car—I don't even worry about individual molecules!

Yet there is some strange tension between knowing that the uncertainty of quantum mechanics governs the universe while simultaneously believing that I am in control of my own molecules. The bioelectric mechanism that is my nervous system allows me to command my limbs, and as a comprehensively certified classical Pilates instructor, I've worked hard to develop my capacity for contrology (as Joseph Pilates called his exercise system). I do Pilates because I am disabled and it helps me manage my pain, but the pain is also a reminder that I don't have total control over my body. Even so, somehow, I have an at least partially deterministic relationship with my body. At the same time, I know that I can never be entirely certain of what a single particle will do in any given moment.

There is some kind of transition from the statistical world of wave-particle duality to the apparent classicality of macroscopic existence—at some point the classical world that we experience in everyday life emerges from the quantum world. This raises the natural question of whether we are magically living in two universes at once. How can classical physics be correct when it does not take quantum physics into account?

Size matters: At the scale of everyday life, quantum effects only govern through statistics that, on average, tend to look rather classical in nature. The length scale where we can expect quantum effects to be significant and dominant is the size of an atom. We need quantum mechanics to explain the structure of the atom—the smallest of which, the hydrogen isotope protium, is comprised of one composite particle (the proton) and one fundamental particle (the electron)—and to explain everything we know about particle physics.

I personally feel that this problem looks even more daunting from the point of view of the relativistic quantum theory of quantum fields. We have many technical words that allow us to talk about quantum field theory, to the point where it can read as though we have constructed an entirely new language. The philosophical challenge associated with interpreting our technical term-laden framework into plain English suggests that quantum field theory is actually very hard to translate. I struggled mightily with how to introduce you to the idea of a field and the difference between a wave and a field. I wondered how to get you to accept that there is such a thing as a wave that does not travel through a medium. Wind in a sugarcane field is easier to visualize than wind by itself. And at the end of the day, wind is the movement of molecules of air. We have a tangible sense of a molecule. A field that has properties that don't exist in real space as we understand it? That's harder to imagine. This question is hard to answer even in the simplest classical example: If the electromagnetic wave is moving, what is it moving *through*?

You might recall that in chapter 6, I noted Maxwell's claim that the magnetic field was a property of a position in space. But every magnetic field also has a source. This suggests to us that maybe, in the QFT framework, a field existing without reference to a source or a medium to facilitate it is missing something. Shouldn't there be a source, an origin? One example of a model that tries to address this is Kaluza–Klein theory, which proposes that we add an additional space-like dimension to space-time, meaning that space-time would have a total of five dimensions. This isn't like another dimension of the "intergalactic planetary," as the Beastie Boys put it. Instead, the extra dimension would be tiny. It would provide structure to the vacuum and function as the medium for fields—whether those fields are electromagnetic, gravitational, the electron, and so on.

Fans of *Star Trek: Discovery* have seen an interesting science-fiction rendering of this idea of invisible dimensions via a transdimensional gay love story (between two scientists!). In season 2, the USS *Discovery*'s physician, Hugh Culber (brilliantly performed by Wilson Cruz), is presumed dead after apparently being murdered at the end of season 1. But it turns out while Dr. Culber was dying at the end of set nonbreaking space between his husband—ship's engineer Paul Stamets (beautifully portrayed by Anthony Rapp)—unintentionally transferred Culber's essence to a fungal network with a kiss. Stamets has a unique relationship with this fungal system—called the mycelial network—because he has been using it as navigator to move *Discovery* instantaneously across long distances.[*] Ultimately, Stamets finds Culber alive—trapped and deeply traumatized in a mycelial network that is falling apart because of how *Discovery* has been using it. The story is a powerful rendering of the devastating impact that war has on soldiers *and* the power of gay love, set in an allegory about the destruction of ecosystems. (The writers were doing a lot at once!)

Culber's storyline is also a fascinating creative invocation of the idea of hidden dimensions. The mycelial network appears to exist in small, extraspatial dimensions that would typically be inaccessible to humanoids. Of course, Cruz's affecting rendering of Culber's emotional trauma is an unrealistic representation of what extra dimensions would be like—and it would have to be multiple extra dimensions, to contain the three-dimensionality of a humanoid. But it does give us a sense of how to think about "locating" them in our own space-time—we cannot see or interact with them, but some of their forces could have significance in the realm we live in.

The bigger challenge for the real Kaluza–Klein theory, however, is that it hasn't translated into testable science—it's a lovely idea, but there is still no experimental evidence to support it yet. There is a plethora of *theoretical* evidence to support the notion that Kaluza– Klein theory is one that could actually work. String theory, which is in many ways an extension of the standard model of physics and its quantum field theoretic framework, builds on the Kaluza–Klein concept. It is rooted in the idea that space-time has a fundamental structure with additional dimensions that are too small to be detectable. In the string-theory picture, particles are replaced with something that we call "strings" but which are true one-dimensional objects. The vibration of each string determines what kind of particle it manifests as. String theory requires space-time to have a minimum of ten dimensions; there are versions with as many as twenty-six. These would be dimensions that are too small for a human to exist in.

As with the simpler Kaluza–Klein theory, there is no experimental evidence that string theory is a correct model of reality. But there are compelling reasons for why people continue to study it. String theory is an example of a model that can successfully explain the origin of the standard model of physics and gravity simultaneously. According to this theory, gravity is quantized and also has an associated force- mediating particle called the graviton—an elementary particle akin to the photon but carrying the force of gravity rather than electromagnetism. How should you visualize this? Good question. Nobody knows! Maybe you're the one who is going to work out what it really means to quantize gravity, or whether a graviton even exists.

Notably, the graviton is not an idea that emerged from string theory. It is actually an idea that will turn a century old in 2034.[2] Almost as soon as a full theory of quantum mechanics had been worked out, people turned to the question of how it could be made consistent with the prevailing theory of gravity, general relativity. Or, vice versa: How could general relativity be made consistent with what we have learned about quantum mechanics? Theories with gravitons present us with one possible answer.

How to Make an Educated Guess About the Fundamental Nature of Reality

One of the beautiful consistencies of physics is that when we aren't sure how exactly to write down a solution to a problem, we may still be able to guess at it based on the information available to us. For example, I know that speed is always expressed in dimensions of length divided by time. When I say "dimensions" here, I'm not referring to the theory that space-time has ten or more dimensions. To understand this particular use of "dimension," it's worth returning to the *Mo Ching* canons and explanations, which I mentioned in chapter 2. Among these works (as translated by Johnston), there is B6, which reads:

> C: Different classes are not comparable. The explanation lies in measurement.
>
> E: Difference: Of wood and night, which is the longer? Of knowledge and grain, which is the greater? Of the four things—rank, family, good conduct and price—which is the most valuable? Of the tailed deer and the crane, which is the higher? Of the cicada and the zithern, which is the more mournful?[3]

Here the Mohists are trying to help us distinguish between phenomena that are directly comparable and phenomena that are not due to their innate physical expression. In the case of wood, when we talk about "length" we are talking about physical size in space. That is one type of dimensionality. In the case of "night," when we talk about length, we are speaking of time. That is a different kind of dimensionality. So we cannot directly compare the length of wood with the length of night, because spatial extent and time are two different types of dimensionality that measure different elements of a phenomenon.

Let's return to our definition of speed: how much distance can be traversed in a given time. Let's say that I want to know how fast something is going, and I don't know what the equation of motion is. But I know that speed is always expressed as length divided by time, so I can guess at the speed if I know some length associated with the system as well as a time associated with the system. This particular type of guesstimating is known to physicists as "dimensional analysis," and it's a pretty valuable skill. I recently gave an exam where a student forgot to write down a useful equation on her equation sheet, but using dimensional analysis—the basis of the first homework assignment I gave the class—she was able to reconstruct the correct equation of motion. That's the power of dimensional analysis!

And it's not just for students. Consider the problem that theoretical physicists face: We know that quantum mechanics seems to describe the cosmos on the smallest length scales. We also know that general relativity describes how gravity works. But we have yet to figure out a data-tested and widely accepted model that merges quantum mechanics and general relativity. As described earlier, we have quantum field theory, which gets us part of the way there as a consistent form of special relativistic quantum mechanics. But gravity remains in the realm of the classical and is not "quantized" in the same way matter is. In general relativity, space-time is not quantized. As we currently understand the big picture, we have all these quantum particles running around doing quantum things in a classical space-time.

Is it possible to learn anything about the quantum nature of gravity? The first thing dimensional analysis teaches us to ask is, "What are the likely scales involved?" We can use the fundamental constants available to us to create fundamental length, time, and mass units—the Planck scale I briefly mentioned in chapter 14. The end result is that the length scale at which a quantum theory of gravity probably becomes experimentally significant is around 10^{-35} meters. In terms of decimals, that's 0.00000000000000000000000000000000001 meters. It's very, very small. Together, these Planck units constitute the values for length, time, and mass for quantum gravity in regimes where the laws of physics as we understand them likely require some modification, because we have to simultaneously account for both quantum- mechanical and general-relativistic effects. We cannot ignore one or the other.

Dimensional analysis helps us understand that context matters. One of my early childhood lessons with this was the song "U.N.I.T.Y.," where Queen Latifah raps about misogynist name-calling and setting a boundary around when certain words, that are typically off- limits, can still be used. "*Now everybody knows there's exceptions to this rule,*" she says. Rules tend to have boundaries—conditions where they apply, and ones where they do not. Dimensional analysis allows us to see when we are allowed to ignore quantum mechanics or general relativity—and when we have to take both of them into account. In both quantum mechanics and general relativity, the question of what constitutes a correct theory of quantum gravity is determined by scientific sensibilities about what such a theory needs. From my point of view, explaining quantum gravity is the biggest fundamental question in physics, because we have these two beautiful pictures that describe the cosmos in incredible detail—and we have been unable to make them work together.

It seems logical that all the laws of physics should be not only self-consistent but also work in concert with each other. The difficulty is in figuring out how. I staked my PhD dissertation on the idea that the phenomenon of dark energy might provide us with a hint about the quantum gravity problem. Another way of thinking about that problem is to ask: How do we connect the boundary-value problem of quantum fields to the boundary-value problem of general relativity? Some string theorists would tell you this is just a sign that we live in the multiverse. Either way, Hawking and Ellis were right that everything boils down to edge work.

The Edges of Space-Times

The "quantum gravity problem" is sometimes conflated with the idea of creating a "grand unified theory" and a "theory of everything." The extent to which these concepts are synonymous really depends on the theory.

I came of age in an era when string theory was quite intellectually dominant in theoretical physics. String theory is an elegant and mathematically elaborate idea that shifts from particles and fields as fundamental forms of matter to a mathematical structure that does not describe literal strings, but has features that Robert Frost might say are understood through metaphor to be string-like. In the context of string theory, quantum gravity truly is a theory of everything, because it provides a unified explanation for the nature of matter and the curved space-time of general relativity.

On the other hand, loop quantum gravity—or loops, as many of us nickname it—takes the view that the general relativistic perspective is fundamental, and simply needs to be quantized. My PhD co-advisor Lee Smolin, one of the creators of loops, writes in his beautiful book *Three Roads to Quantum Gravity* that loop quantum gravity and string theory might actually be two sides of the same coin and will eventually lead to the same theoretical framework.[4] One manifestation of the idea of loop quantum gravity is the concept of spin foams, which are built on the idea of space having a minimum length scale and a fundamental sense of discreteness. A rough way to visualize this is to think about a piece of graph paper and imagine that space- time is broken into discrete little boxlike pieces at the smallest scales. This model requires us to let go of the idea that space-time is continuous and that every point in space-time is touching another point. It fundamentally respects the idea of a minimum Planck length scale, while also adjusting our traditional general relativistic notion of space-time.

But neither spin foams nor any other form of loop quantum gravity gives us an explanation for the standard model, which means that these theories take a very different approach to the question of exactly what a quantum gravity model must do. They are not a grand unified theory or even necessarily a theory of everything. I think loops answers the question of quantum gravity very literally, looking for a quantum theory of gravity. String theory takes a more expansive approach, rooted in searching for a comprehensive theory that builds on the unification of the standard model of particle physics. The graviton theory, meanwhile, would bring gravity into the standard model and allow it to cover all four forces instead of only three.

But the standard model isn't the only element of the universe that needs to be accounted for. There's also dark matter and the vacuum energy. The whole universe, space-time included, needs to be in there too. Ideally, any theory of quantum gravity—and especially a theory of everything—will include a complete model of quantum cosmology. What does this mean? Exactly what it sounds like. One way to arrive at quantum field theory is to consider the need to bring special relativity and quantum mechanics into conversation with each other. But another way to arrive at it is to ask questions about how to simultaneously describe the quantum properties of a large number of particles that are in a shared system or state. We already have a notion of a wave function that corresponds to a single particle, which can be extended to a multi-particle scenario. We already think about multi-component quantum scenarios. Why not extend this idea to include the whole universe? What is the wave function for the whole universe?

The observer presents one of the challenges in trying to figure out quantum cosmology: What happens when a system tries to observe itself? In quantum-mechanical laboratory experiments, that's not what happens; the observer is always something external to the experiment, even if it is another instrument. Back in chapter 9, I highlighted some of John S. Bell's thoughts about this. He was deeply troubled by the conclusion that the observer could actually cause a system to select a status, as if the universe were simply waiting for us to come along and look at it. A complete theory of quantum cosmology will be able to navigate the unique way this measurement problem manifests when trying to cover the entire universe, observer included.

I have already briefly discussed an attempt to answer these questions in chapter 10. There, I mentioned Thomas Hertog and Stephen Hawking's efforts to develop a full theory of quantum cosmology using the idea that when a particle moves from one place to another, quantum-mechanically we have to calculate the possible outcomes using all possible pathways the particle takes. Their idea, first proposed in a jointly authored 2006 paper, "Populating the Landscape: A Top-Down Approach," relies on a concept from string theory that has both scientific and cultural ties to the cosmic acceleration problem—our difficulty explaining why the expansion of the universe is speeding up.[5]

If we treat the existence of cosmic acceleration (see chapter 13) as a measure of the vacuum energy, which is then characterized as the cosmological constant, then what we really have to explain is why the constant has the value that we measure. When I first told you about cosmic acceleration, I mentioned the anthropic explanation for it. The anthropic principle is the idea that we humans wouldn't be here to observe the universe if the cosmological constant had another value. I have a deep-seated dislike of this approach to solving the problem, but I try very hard to be an adult about it, so let me explain why it is rational to consider it. One interpretation relies on the preposterous idea that the universe is organized around us. But another interpretation is that, on some level, the whole universe is just a happy accident. A universe happened to form with the right conditions such that we could exist, and happily we are here—a part of it and also observing it.

Trying to make sense of how we end up in the universe with the right values of the fundamental constants needed to create the conditions for life is itself a measurement problem. String theory predicts that there are many possible universes, all of them with different cosmological constants. This is known as the *landscape,* so named because it is (metaphorically) a whole landscape of possible universes. It's an idea that provokes an immediate challenge: How many universes are like ours? Is our iteration of the universe unusual? Why does this one exist? So far, string theory has not offered us a solution to this challenge, which is an example of a fine-tuning problem. It seems that in order to get the universe we actually live in, we need to specifically pick the right parameters to get it, rather than have it naturally arise from our theory. We have to literally fine-tune the universe on paper to make it work for us. Ideally, we wouldn't have to do this, or pick and choose in this way, because the theory would simply tell us.

String theory isn't the only place where different plausible scenarios arise. In chapter 4, I briefly mentioned the phenomenon of eternal cosmic inflation, in which inflation happens continuously throughout a larger multiverse full of different space-time bubbles. In this schema, our space-time bubble is one of a possibly infinite number of others. This is one way that a multiverse leaps off the theoretical physics page—a realistic if extremely difficult-to-test possibility. And it comes with the same problem as the string-theory landscape: How do we figure out how common a bubble like ours is? This is called the measure problem, which (though similarly named) is not actually the same as the measurement problem!

One way to think about how this manifests is to consider the Summer 2024 rap battle between Kendrick Lamar and Drake. In our universe, the beef ended very badly for Drake, who really should have quit after Lamar released the song "Euphoria." Drake's defeat was undeniable—even his fans know he lost (and should, by the way, reconsider their allegiances). In the multiverse of eternal inflation, there are some universes where these two rappers never come into existence. And there are universes where they both exist and this rap battle occurs with exactly the same (correct) outcome that we witnessed in 2024. But there will also be some universes where the opposite happens; where maybe Drake is the talented one. Currently we have no way to calculate the ratio between universes where Drake is revealed to be the empty suit that he is and the ones where he (bizarrely) comes out on top—this is the nature of the measure problem. Ideally, our theory of quantum gravity would naturally offer us a solution to it. But as we've seen, the most elaborate theory of quantum gravity so far seems only to offer us a different version of the same problem.

Returning to Hawking and Hertog, their goal was to develop a physical theory that could address the existence of the landscape as well as the fact that there don't seem to be any boundary conditions that might establish how the string-theory landscape gets pared down to the universe we live in. Notice how boundary-value problems snuck in there again? Another way of thinking about the quantum nature and quantum history of our universe is by trying to understand both the universe's initial conditions as well as what boundary conditions should be applied to a theory of quantum gravity. Yes: In the end, every physics problem is a boundary problem; all cosmology questions are about the all-important edge of space- time. The revolutionary idea in Hawking and Hertog's model is that instead of assuming the universe has one classical history, their model assumes there are instead a plethora of possible histories that must be used to establish the history of the universe. They claim that the result is a calculational framework where the only boundary conditions that need to be known are from now—that none from the past are needed in order to establish how we arrived at the moment we currently live in.

It's a tantalizing model that remains incomplete. But even if it turns out that it doesn't work, I like it as a kind of proof of concept. This is the kind of creative thinking we should be doing. And I hope that, just as the Kaluza–

Klein theory did for the writers of *Star Trek: Discovery,* Hawking and Hertog's theory will also inspire interesting works of art that become part of what makes humanity a species worth saving.

Visual culture has also provided inspiration for researchers thinking about finding the right tools to solve the quantum gravity problem. In 2005, Michael Faux and Sylvester James Gates proposed that West African adinkra, like the Sankofa symbol, could potentially offer us a new mathematical framework to solve open questions in particle physics and quantum gravity.[6] Their original proposal focused on the theoretical extension of the standard model known as supersymmetry, an idea I introduced in chapter 14. The fundamental concept at work here is that the structure of the adinkra symbols can provide a helpful graphical representation of supersymmetry—a key ingredient to string theory—and allow us to see and think about it differently. With this model, Gates, who is Black American, put into practice the idea that our cultural perspectives can shape what scientific theories we conjure. The adinkra framework can also be extended to supergravity, a quantum gravity proposal that combines supersymmetry and general relativity. This is yet another theory where there is no empirical evidence to support its correctness, but it is nonetheless a fascinating possibility.

Finding the Answers in the Places Where They Disappear

In the absence of experimental evidence to sway us—which means assuming cosmic acceleration doesn't count—the best place to look for quantum gravity is in a black hole. This might sound surprising, since black holes are supposedly where stuff goes to never be heard from again. But as you now know, that's not quite correct. And it turns out that black holes are extremely useful canvases that help people generate ideas that are helpful across physics, including in the realm of quantum gravity. This is quite logical, since they are in fact places in the universe where gravity is at its strongest and where there are notable quantum-mechanical effects. A quantum theory of black holes reveals exciting new phenomena.

Black holes are also a useful thinking tool because—like the larger universe—they have a horizon beyond which information is supposedly inaccessible to us. Remember something we discussed in chapter 4: On the largest scales, space-time has a particle horizon and a cosmic event horizon. This is obviously a very different phenomenon from a black hole's event horizon, because a particle horizon is the location that is so far away from us that our part of space-time never could have been in contact with it. It is defined relative to our position, and nothing happens if we somehow manage to get across it; the space-time should be the same. A black hole's event horizon, on the other hand, is a specific location in space-time where the nature of the space-time changes quite dramatically. Even so, the insights we gain from studying black holes can provide us with insight into the structure of our larger space-time. So one can think of understanding the quantum nature of black holes as a baby version of this larger problem, which will hopefully provide insight into how a good theory of quantum gravity would work.

One related idea that scientists have been especially excited about over the last few decades is the holographic principle. A hologram is a three-dimensional image that is created using a two-dimensional surface. In the case of black-hole holography, the proposal is that any theory of quantum gravity in which a black hole appears should be described not through the lens of three spatial dimensions and one time, but instead two spatial dimensions. To visualize this, think about a perfectly round billiard ball. When we describe the billiard ball mathematically, we want to take into account that it is three- dimensional. But in reality, the part that interests us when we look at it is only the surface, which is two-dimensional. If we peel the surface off the ball and cut it open, it will look like a (strangely shaped) piece of paper. The proposal behind the holographic principle is that quantum gravity should only be formulated in a lower dimension, forced to exist on the lower-dimensional equivalent of that strangely shaped piece of paper. In this model, any universe with black holes should be described by a quantum gravity that obeys this precept.

Imagine that—a universe where our most elaborate theory has to live in fewer dimensions than we do! And if you're wondering why you should care, the fact that we are even being invited to imagine such a scenario is the whole reason why. It matters whether we live in a world where we are inspired by strange new worlds of ideas. Fundamental physics offers us endless, surprising, queer, and at times deeply frustrating perspectives on our world. There's incredible intellectual power in that, yes. But there is wonderful spiritual power in it too. To be an engine of human creativity is to be in conversation with what makes us *us*.

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* Stamets is named for the real-life mycologist (mushroom expert) Paul Stamets. And the idea of instantaneous leaps across space-time parallels a solution to the cosmic acceleration problem that I proposed as part of my PhD work. To read more about cosmological nonlocality, see chapter 3, "Spacetime Isn't Straight," in my book *The Disordered Cosmos*. This idea is where the phrase "disordered cosmos" comes from.

Go to note reference *

IV.

LET'S FLY

CHAPTER SEVENTEEN

COSMIC ENERGY

In which we realize we don't understand energy, not really

The universe might be the ultimate free lunch, but for humans, what to do about energy—how to get it, how to store it, how to use it, and how much of it to use—is one of the most urgent questions of our time. You could argue that it has been a pressing concern for most of human history, but never before has answering it been a matter of life and death for not only our species but also possibly all life on Earth. Yet despite the intense political challenge it presents, the actual phenomenon of energy is not particularly well understood. As a practice, cosmology can give us a sense of continuity and connection by threading together how we are all part of one story, and the same is true of energy.

I started thinking about this in part because of the original 1922 Stern–Gerlach experiment. Silver atoms are made into a nice column of flying atoms by passing them first through a circular hole in a metal sheet and then a slit in a metal sheet. Both metal sheets were made of platinum in the original experiment. More recently, the undergraduate physics major junior lab at MIT has used platinum as part of the detector in the experiment where students reproduce the Stern–Gerlach experiment for themselves. It's easy not to think too deeply about where the supplies for these experiments come from. When I took my junior astrophysics lab at Harvard, as far as I knew, the supplies for our photon-detection experiment originated in the lab, which got them from some supplier—and I honestly didn't think much about it. I didn't consider what Shawn Wilson (Opaskwayak Cree) records his uncle as observing in the book *Research Is Ceremony:* that all of the technology we use still has its origins in the land, even if it has been transformed by human hands.[1]

But when I first started thinking about teaching the Stern–Gerlach experiment as a professor, reading about the use of platinum stood out to me. Where had the platinum come from? I was prompted to ask this question thanks to a former student. In my Introduction to Astrophysics class, all of the undergraduates are tasked with making a final presentation about the cosmic history of an atomic element: how it is made, what its properties are, and a bit about human history with it. I've learned a lot from these presentations. One of my students chose platinum, and from their presentation I learned that Europeans didn't really know about platinum until the 1500s, when they were first beginning to study the area where Aztec and Mayan people lived. The Europeans wrote platinum off as crappy, valueless silver that made gold impure. (That's why the word "platinum" comes from the Spanish word "platina," which means "little silver.") Only in the 1700s, when some Spaniards learned that Indigenous people were mining it, did they consider the possibility that it was useful and valuable.

As I reconsidered the construction of the Stern–Gerlach experiment, I wondered whether the platinum it used came from Latin America. I wondered how Gerlach knew to use platinum, and by what pathway the platinum in his lab arrived there. I have been unable to work out the answer, although it's possible the platinum was from Dutch and British colonies in Southern Africa, where new mines had opened just decades before Gerlach undertook the experiment. Around the same time, I also began to familiarize myself with the conditions of Black South Africans in the early and mid-twentieth century to better understand that the Indigenous peoples of Southern Africa, like the Indigenous peoples of Latin America, were akin to enslaved people in the mines. I wondered if the Stern–Gerlach experiment had been supplied by enslaved people. How did the cosmos arrive at a place where enslaved Indigenous people are pulling stellar remnants out of the ground in a process that is often toxic for the land? What would it look like to change our world so that mining isn't a toxic, inhumane activity? Is that even a possibility?

Platinum is highly prized today because it is rarer than metals like silver, it's very adaptable, and it's strong. People appreciate all the ways we can use it, whether in a physics experiment or as adornment. But we could look at its value in another way—how it invites us to more fully understand the cosmos.

As If We Even Understand Energy!

To fully answer the question of where the platinum in an experiment comes from requires going back to the beginning of everything. And people like the late musician, visual artist, and technologist Milford Graves have been trying to tell us about this. A product of the multinational Black community that populated 1940s New York, Graves came to believe that "cosmic energy [is] circulating in the air," and that whatever plants are photosynthesizing is in fact cosmic energy.[2] I suspect that when other scientists watch the 2018 documentary *Mil-ford Graves Full Mantis,* they readily dismiss his comments as woo- woo artist vibing disconnected from the inner workings of physical reality.

But I believe Graves understood that the story of cosmic energy is the story of us. We presume that cosmic inflation was followed by an era of particle creation, where the dregs of the inflationary field gave their energy to the quantum fields whose excitations became the first electrons, quarks, neutrinos, and photons. These particles formed into what could be accurately described as hot plasma stew. Importantly, part of what must be achieved during this era is the reheating of the universe after extreme cooling by rapid inflation. Notice the significance of energy in the story we tell: It's there, over and over.

The irony of our complete dependence on energy as a concept is that we don't fundamentally understand it. Like space, like time, it is an abstract idea that feels real and is wildly useful, but it's also rather slippery and resists simple definitions—like everything else in physics, it turns out. Energy is easy to talk about and even to have intuition for, but in my opinion, disgustingly difficult to define in a satisfactory way. Etymologically, the English word for energy comes from the Greek for "activity," ἐνέργεια. This is not a terrible definition. Energy is how much capacity for activity a system or object has, whether that activity is occurring or only could potentially occur. When the activity is occurring, the associated energy is called kinetic energy, the energy associated with motion. When the motion is only potentially going to happen, the capacity for that activity to occur is known as potential energy.

But what is "activity," really? Energy has always felt impossibly tautological to me. *Merriam-Webster* offers this physical definition for energy: "a fundamental entity of nature that is transferred between parts of a system in the production of physical change within the system and usually regarded as the capacity for doing work."[3] I learned from this definition that "entity" effectively means "thing that exists"—so energy is a fundamental thing that exists. But that's a declaration that provides no insight into what it really is. The rest of the definition says that energy is a thing that can be "transferred between parts of a system" through a process that is related to creating change in the system, which in physicist terms is directly correlated with the "capacity for doing work." Overall, I would say this is a functional definition which also exemplifies the way in which energy is an abstract concept, not an idea that is immediately accessible just through our senses.

If you want to know what energy is, don't go looking in a physics textbook. My favorite definition of "energy" goes to the user *causative* on the Philosophy StackExchange website.[*] They explain: "Rather than a 'thing,' it's better to think of energy as an attribute that things—or arrangements of things—can have, which is conserved among interactions between things." This feels right to me. Energy is an attribute, a characteristic of an object. And it is not a fixed attribute, but rather one that can change with time, with physical conditions. This definition also points to how that attribute works, a rule known as the first law of thermodynamics, which posits that energy is neither created nor destroyed.[†]

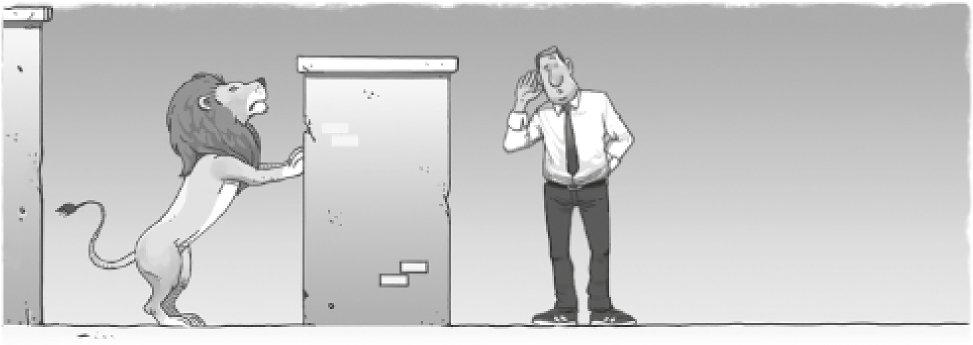
The first law of thermodynamics is perhaps more popularly known as the concept of "conservation of energy": Energy never goes away; it always goes somewhere. This is consistent with special relativity, which teaches us that matter and energy are equivalent, and that in some sense everything truly is energy. This is also consistent with and in fact a consequence of the Emmy Noether law you encountered earlier, in chapter 5, which says that where there is symmetry, there is a conservation law. Energy conservation is associated with time- translation symmetry, which simply means that if I change the time interval during which a phenomenon happens, everything will still unfold exactly the same. Energy is an attribute that is conserved as systems unfold and interact, although the form it takes may change. And the way energy changes form is informative for us. In fact, one way of thinking about the practical task before a physicist is to follow the energy.

When we say that energy is conserved, we mean the total of the kinetic energy plus the potential energy. And we tend to think of potential energy as converting into kinetic energy. In the case of the electric Coulomb force, there is a potential energy associated with the force called the electric potential. The potential becomes kinetic energy when it interacts with a charged particle or current. Similarly, there is a potential energy associated with gravity. Before I drop my peanut butter jar on the floor, it's full of gravitational potential; once in motion, that energy becomes kinetic. As Milford Graves was constantly working on new ways to show, cosmic energy is everywhere.

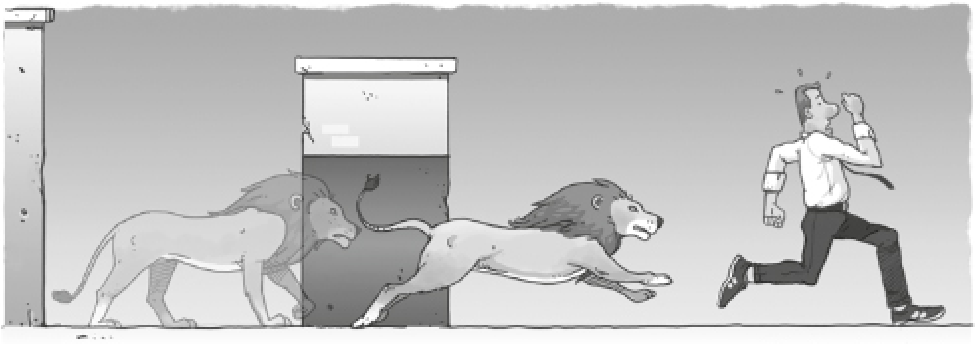
We Are All Stardust

Star formation is also a story of energy. Clumps of hydrogen can form if their local Newtonian gravitational attraction is stronger than the pull of stretching space-time. As time goes on, the hydrogen atoms in these clumps bind ever more tightly as gravity continues to work on them. The gravitational potential of the system is converting to kinetic energy, energy associated with movement. There is also a kinetic energy associated with the arrangement of the atoms themselves. Helpfully, knowing the total energy of a system allows us to write down information we might like to know, like the equation of motion. If there is enough hydrogen gas collected into a small enough space, it might get so hot and massive that the proton-neutron nucleus of hydrogen is squeezed very close to lots of other nuclei like it.

Because the protons have the same charge, they electrically repulse one another. But we know that the strong force that binds nuclei is stronger than this repulsion, if the particles are close enough together. Getting the particles in close quarters is a matter of quantum mechanics. The conditions are so hot, and there are so many atoms involved, that a process called quantum tunneling will happen. In quantum tunneling, a particle that is up against an energetic barrier it can't get through (like electric repulsion) will sometimes get through anyway because of its quantum nature. There's a small statistical probability of the particle ending up on the other side of the barrier. This means that the particles will overcome the barrier of the electric energy pushing them apart and get close to each other anyway (see Figure 17.1). In a universe governed by quantum mechanics, the impossible becomes plausible.



Classical Mechanics



Quantum Mechanics

Figure 17.1. Quantum tunneling means that there is some possibility that impossible things can happen anyway. Think of the lion like a particle. Classically, when it hits a wall, it can't get past it. But a quantum particle, when it hits an energetic barrier, can sometimes end up on the other side, anyway. So, that man better run!

This tunneling is a purely quantum effect, not feasible in classical mechanics or with electromagnetism. Now we have a situation where two nuclei have merged: They are no longer two hydrogen atoms but instead a helium nucleus, along with a tremendous amount of energy released through the merger process. And now there are photons and neutrinos that did not exist before—matter has taken on new energetic forms. This is nuclear fusion; when it happens frequently enough, it is the beginning of stellar nucleosynthesis. This is how a star is born, a story we were first able to put together thanks to Cecilia Payne-Gaposchkin's recognition from early spectrographic data that stars were mostly hydrogen and helium.[*]

For the next million to trillion years—depending on the mass of the star—fusion processes like this will cause the star to continuously produce new photons across the electromagnetic spectrum. A star like our sun will live for 10 billion years, at first converting most of its hydrogen into helium before entering a helium-burning phase. Here we use "burning" a little bit loosely, because what we really mean is that helium atoms are undergoing nuclear fusion. When a star burns helium, it produces carbon, oxygen, and nitrogen. A star like our sun will go on to produce atomic elements like neon, silicon, beryllium, magnesium, nickel, niobium, cobalt, and everything else between hydrogen and iron. All of this is possible because of matter-energy equivalence, and also because protons and neutrons are not fundamental particles; they are instead composites of up and down quarks. This makes it possible for neutrons to become protons, and every time a proton joins an atomic nucleus, it changes what type of atom the nucleus is. That's how a star cooks up more and more massive atomic elements. This atomic transmutation is made possible by the weak nuclear force and the associated beta decay, a phenomenon that was first established in the lab by Chien-Shiung Wu, in the decade before she contributed to the Manhattan Project.

Iron is the limit of what a star can make in large amounts before it no longer has the conditions to fuse. This is a sad time for what the object was, but an otherwise exciting moment: In the case of a star like our sun, a white dwarf forms in the center, while the outer layers become a halo of gas surrounding the white dwarf. Humans call this a "planetary nebula" for historical reasons; there is no actual planet involved. The Ring Nebula that I imaged with my telescope and shared with you earlier is an example of such a system (Figure 11.1 in the photo insert). You can't see it in my photo, but there's a white dwarf in the middle, the leftovers of that star's core.

Stars that are at least eight times more massive than the sun will have an even more brilliant ending: a supernova. It's helpful to recall that a Type Ia supernova can be caused by a white dwarf accreting a companion star until it has a runaway chain reaction and explosion. An alternative path to a supernova is when a massive star hits a point where so much of its mass has been converted to iron that nuclear fusion is no longer sustainable. While fusion is happening, there are forces that counterbalance against gravity—

there is pressure due to electromagnetic radiation produced in the nuclear reactions. Fusion also keeps everything hot and moving fast. When fusion shuts down, suddenly there is no force working against gravity anymore, and the outer layers of the star collapse down onto the core. The core, meanwhile, has turned into a compactified collection of neutrons (and probably some quark soup) while emitting neutrinos and high- energy photons like gamma rays. The outer layers of the star cannot be absorbed by the core due to strong-force interactions, and this causes a short-distance repulsion between neutrons. The end result: a shock bounce! The outer layers of the star bounce off the core, leading to a visibly spectacular shock wave.

This phenomenon is called a Type II supernova, and it makes an important contribution to the cosmic kitchen. First, it is how neutron stars are made: The core that is left behind is the densest object in the universe—imagine squeezing the entire mass of the sun in the middle of Los Angeles. To get a sense of how dramatic this would be, keep in mind that over 1 million Earths can fit inside the sun. The sun takes up a lot of space! Also note that it would take over 300,000 Earths to get to the mass of the sun. So imagine fitting 300,000 Earths into central Los Angeles: That's a neutron star. If you've ever dreamed of looking at the hot plasma stew of the early, Big Bang–era universe—and you should!—neutron stars are the closest the universe gets to maintaining those conditions. The extremely dense conditions of a neutron star also mean that it may be an environment where quarks move around unbounded. As you can see in Figure 17.2, we don't know exactly what the interior of a neutron star is like.

For the last several years, a group of us have pursued a better understanding of neutron star interiors using a small X-ray telescope that is attached to the International Space Station. The Neutron Star Interior Composition ExploreR (NICER)'s mandate is to gather data about neutron stars that allow us to, among other things, deduce the mass and radius of individual stars. Each nuclear model of neutron star interiors makes a distinct prediction of what the relationship between the mass and radius will be; with measurements from NICER, we can rule out models that don't fit its observations.

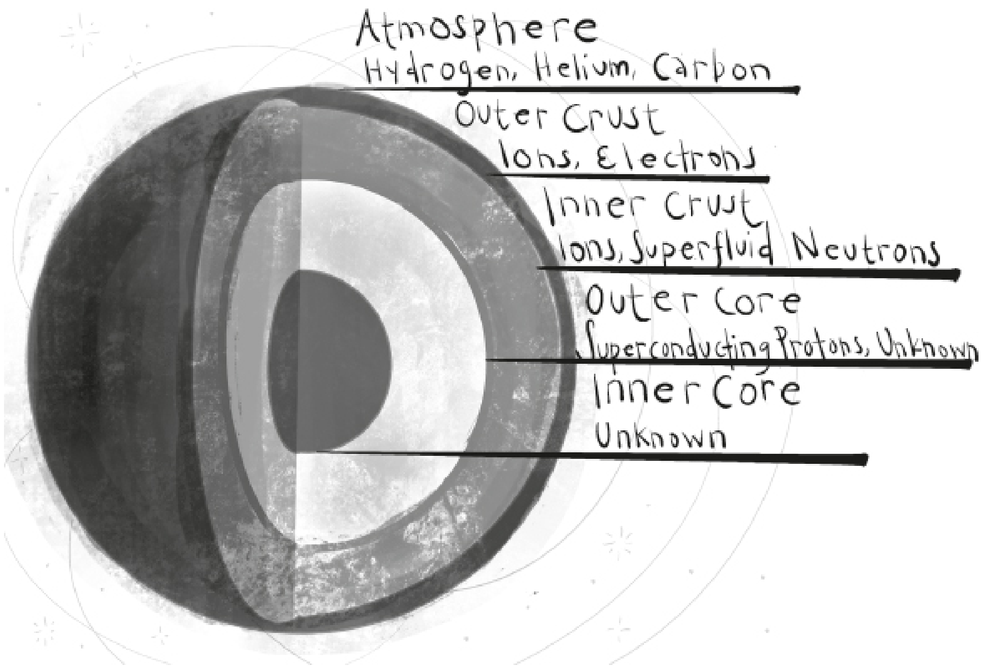


Figure 17.2. Here's a figure that shows what we *think* a neutron star is like in its exterior layers. The inner core is unknown.

I initially became interested in this work because the intense gravitational power of neutron stars' high density suggests that they might collect dark matter. This is an idea that my former PhD student, now Dr. Nathan Rutherford, has pursued under my direction, in collaboration with Professor Anna Watts and Dr. Geert Raaijmakers at the University of Amsterdam. So far, what our work shows is that all NICER data is consistent with the presence of dark matter, but we have been unable to demonstrate that we can use mass-radius relation measurements of neutron stars to prove that dark matter is inside.[4] What this means in practice is that all data analyses should consider the possibility that dark matter is present, but it's unlikely that this will be the technique that identifies dark matter's exact field- theoretic properties (such as mass and standard-model interactions).

Neutron stars and the supernovae that make them are important for another reason: Without them, we wouldn't get the heavier atomic elements that are part of our everyday life. Since stellar fusion necessarily stops at making iron, and there are many more elements on the periodic table beyond iron, the energies required to produce more massive elements comes from supernovae and their sometimes more powerful siblings, kilonovae.[5] Kilonovae occur when neutron stars collide or a neutron star and a black hole collide. We've come to study kilonovae more deeply since 2017, when we first detected gravitational waves from this kind of collision. Since then, astronomers have estimated that at least half the gold in the universe is probably made in kilonovae, although there is ongoing debate about the balance between supernovae and kilonovae. Though gold has been more of a focus of research, the expectation is that this is also how atomic elements that are of interest to humans—like silver, platinum, uranium, niobium, and tantalum—are made in abundance.

While you may have heard of silver, platinum, and uranium (the latter of which is used for both nuclear weapons and nuclear power plants), perhaps tantalum (atomic number 73) and niobium (atomic number 41) are less familiar to you. Both have important technology applications: If you own a smartphone or a computer, you own some tantalum. If you've ever undergone magnetic resonance imaging (an MRI), you've benefited from a machine that uses niobium. Tantalum and niobium are among the many atomic elements that play a major role in our lives but which we typically don't hear much about.

Becoming Stellar Caretakers

All of these elements are different manifestations of the energy that had its beginnings in the Big Bang. As Milford Graves worked out over decades while exploring the universe through drum and heart rhythms as well as martial arts and other movement practices, cosmic energy is indeed circulating around and working through us. Everything we are made of began and eventually will return to cosmic energy. And that means that we are called to be thoughtful energy producers and users.

There is a limited amount of every atomic element in the universe, although there is a high abundance of hydrogen. Most visible matter is in the form of hydrogen. The supply we have of everything on Earth is even more limited. Even in the case of cosmically abundant helium, most of the Earth's supply comes from nuclear decay in the Earth's crust, which happens at a limited rate. We have to mine our helium, and as I mentioned earlier, we have a global shortage of it. This has implications not just for birthday balloons—which are bad, please don't get them—but also for health care:

Helium is needed to supercool important tools like the magnets in MRI machines, which have saved many lives.

Of course, in the era of encroaching global warming, there are other vital considerations regarding how we use the stardust—and primordial helium and lithium that formed in the early universe—that are available to us. We've been promised that lithium batteries are key to a greener future because they can store solar energy and allow us to move away from gas combustion engines in consumer vehicles. But there is a price to be paid, since lithium must also be mined through a process that is often highly toxic to the local land and water supply. And the power dynamics associated with it today are the same as they have long been in a white-supremacist colonial system: The Global South serves the Global North, often at the expense of Indigenous communities.

Indigenous peoples across Latin America are not passive in the face of this latest threat to their sovereignty. They have been organizing against increases in lithium mining, what they term *extractivismo,* which threatens their ecosystems and represents yet another attack on their sovereignty. Political scientist Thea Riofrancos has done work that shows there is real tension between people who believe that the Global South can only become independent from neocolonialism through extractive mining activities, and people who don't want economic development to come at the expense of the land or its people.[6] They are rightly raising the question of how anyone can possibly save life on Earth by doing things in the same exploitative ways as colonizers.

In the specific case of tantalum and niobium, both are found in the Earth's crust in an ore known as coltan. The largest producer of coltan in the world is the central African Democratic Republic of the Congo (DRC), and as I wrote this book, organizers there were calling attention to how mining for coltan, diamonds (which are pure carbon), zinc, and gold drives genocidal violence in the region. Reports say that up to 6 million people have been killed, with an almost equal number displaced, the violence meted out by armed militias seeking control of mining profits. Economists have estimated that these mineral resources are worth up to $24 trillion, and the global coltan market is worth over $1 billion.[7] And as with enslavement in gold mines under South African apartheid, coltan mining—which is done by hand—is fraught with labor abuses, including extensive use of forced child labor. Enslavement powers our computing devices. The mining is also highly toxic to the environment.

It is easy to read about these horrors and feel helpless. *I can't just stop using my iPhone,* you might be thinking. Here I find political scientist Benjamin L. McKean's call to think about how we orient ourselves helpful. In his book *Disorienting Neoliberalism,* McKean writes that part of how our modern capitalist economic structures work on us is by making us think that everything is about how we respond as individuals.[8] But what if we reoriented toward responding as communities, toward working with others to address problems? Anti-genocide organizers have asked people to stop replacing their perfectly functional iPhones when an upgrade is not necessary. This applies pressure on companies like Apple to develop a more ethical pipeline. As historian Gabrielle Hecht outlines in *Residual Governance,* part of this ethical pipeline will include thinking through how waste associated with mining is managed, a problem that nuclear energy advocates must also address.[9]

In *Planetary Mine,* sociologist Martín Arboleda argues that reorienting our relationship with mining requires a new "planetary" analysis of labor, one acknowledging the fact that the labor of manufacturing and mining cannot be separated. He urges us to engage in "a process of conceptual experimentation that can transcend the limitations posed by" traditional models of considering the economy, resource use, and whose cultural values take priority.[10] He goes on to identify a crucial link between these challenges and the practice of science, noting that intellectuals are increasingly suspicious "of contemporary science, especially a model of scientific knowledge that subordinates the totality of their skills, capacities, and positionalities to the immediate needs of profit-making."

Whether those of us in particle physics, cosmology, and astronomy like it or not, we are caught in this web. Understanding the majesty and poetry of our cosmos is a political process. We have a responsibility to recognize that not only do our technologies depend on these minerals and the labor required to extract them, but also our funding has always been linked to the needs of the military-industrial complex and capital needs. As the military-industrial complex and capital move on to new favorites—for example, so-called artificial intelligence and quantum computing—we are feeling a resource squeeze. We are also being pressured to reorient our PhD programs into data science and AI training programs for workers that will enter industry. The stars are consciously being recategorized as a training ground to serve capital interests.

But queer, Afrofuturist artwork invites us to imagine other possibilities. The 2021 Saul Williams and Anisia Uzeyman–directed film *Neptune Frost* explores what liberation looks like for coltan miners in Burundi, which shares a border with DRC. In the world of *Neptune Frost,* gender is not binary, queer love is a norm, and a revolutionary group of people have found a kinship with the elements that they mine, calling to mind Shawn Wilson's uncle who said his laptop comes from the land. In the movie, the miners chant, "The miner is everything! Dig! The miner is the power source! Dig! Alone but not alone."[11] At one point, a character reminds us: "We power the system. It is the same energy which flows through us."[12] *Neptune Frost* invites us to imagine a world where the people of the land make decisions about how to mine, under conditions that honor and do not ignore their humanity. The hero's journey of the intersex lead character, the hacker Tekno, is a reminder that we choose what kind of caretakers we will be for the cosmic energy around and within us.

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* You can find their entire answer here: https://philosophy.stackexchange.com/a/85904.

Go to note reference *

† And, coincidentally, was identified *after* the second law of thermodynamics that I discussed in chapter 10, "Quantum Sankofa."

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* For more on Payne-Gaposchkin, check out: Moore, *What Stars Are Made Of,* and Sobel, *The Glass Universe*.

Go to note reference *

CHAPTER EIGHTEEN

YOU ARE NOT SAFE IN SCIENCE

In which we consider going to space to escape ourselves

Halfway through *Space Is the Place,* Sun Ra muses that scientists are fed on research while Black people have been fed on freedom. As a Black physicist, I have been fed on both, and I have tried to grow the seeds that my ancestors passed on to me. The ancestors could fly. I do too, whenever I am able to escape into looking at the universe through the lens of quantum fields. I am not the first to escape into the abstractions of space and time. If you've read this far, then you have joined me. We are not the first. We will not be the last.

When I was younger, I knew I could be a scientist because I grew up watching LeVar Burton play one on television. As Geordi La Forge, chief engineer of the starship *Enterprise* on *Star Trek: The Next Generation,* Burton gave us a brilliant, Black nerd. Because I saw this early example, my child self never doubted that I had the freedom to be a professional nerd too. It was not a possibility that was, as it had been for Black generations before me, "Far Beyond the Stars"—the title of a powerful episode about twentieth-century anti-Black racism that aired during the sixth season of *Star Trek: Deep Space Nine*. *DS9,* as many fans know it, was the first *Trek* series to feature a Black lead. Avery Brooks's Benjamin Sisko broke barriers in what is to this day the longest-running television drama with a Black man in the leading role. Like Burton's Lieutenant Commander La Forge, Captain Sisko taught Black children like me that not even the sky was the limit.

In this sense, representation has real material meaning: *Trek* has continuously pushed the boundaries of our imaginations for as long as it has existed. Burton's performance as Geordi La Forge has its origins in an earlier iteration of *Trek*—the first Black person Bur-ton ever saw on television was Nichelle Nichols as Lieutenant Nyota Uhura in the original *Star Trek* series. This milestone was marked in the January 1967 issue of *Ebony* magazine, which also features a cover photograph of Nichols. In the photo, she's wearing a form-fitting red synthetic velour dress with a respectably high black scoop-neck collar—the uniform of a liberated Black woman who is Earth's chief communicator in outer space. The dress looks straight out of the 1960s except for the small patch over the left breast, which is roughly shaped like an arrowhead and features a swirly letter *e* (for engineering). The accompanying feature story declared that Nichols, then a star of the brand-new NBC Color television show *Star Trek,* was "the first Negro astronaut, a triumph of modern-day TV over modern-day NASA."[1]

The decision to feature the stunningly beautiful Nichols on the cover, complete with a lengthy feature describing her significant contributions to the production of Gene Roddenberry's new humanistic drama of life in space, was both clear and pointed. Not only was *Ebony* celebrating a great Black actor; it was also offering political commentary on the whiteness of the political zeitgeist, asserting that NBC had imagination NASA utterly lacked. Of course, there are limits to this way of looking at things. Roddenberry had filmed the first *Star Trek* pilot featuring white actress Majel Barrett (his wife) as second in command of the *Enterprise,* but NBC hated the idea of portraying a white woman in such a powerful position and refused to pick up the series. The franchise might have died were it not for the intervention of Lucille Ball of *I Love Lucy* fame, who insisted that Roddenberry be given a second chance. So Roddenberry got rid of the white woman first officer and replaced her with not just any male but a male alien: Leonard Nimoy's science officer Spock. He also added pilot Hikaru Sulu to the crew, played by Japanese American concentration-camp survivor George Takei. And he cast Nichols, already a star stage performer, in the role of the communications officer whose last name recalls *uhuru*—Swahili for "freedom."

It would be nearly three decades before a Black woman would finally make the journey to space in real life. Roddenberry, of course, was not the first to dream of it. I imagine that Black women have dreamed of space throughout the centuries—for much longer than the idea of "Black people" has existed. Even *Star Trek* was a few years behind journalist Edward Murrow, who, as head of the U.S. Information Agency, wrote to NASA administrator James Webb in 1961 to suggest that the United States send "the first non-white man to space." Webb replied that such a choice was "inconsistent with our agency's policies."[2] And so in 1967, it was Lieutenant Uhura who first fulfilled that dream in the popular consciousness. Beamed into the living rooms of Black children across the country, Nichelle Nichols transformed how Black children saw themselves and their futures.

Media like *Trek* kept me open to the possibility that space represented. I am a child of the space shuttle era, so I never knew a world where humans, including Black people, weren't annually flying to space. I was fascinated by the 1976 IMAX film *To Fly!*—and saw it at both the California Science Museum and the Smithsonian Air and Space Museum in Washington, D.C., where it brought me "past Mars, past Jupiter and its moons, past Saturn and beyond." The script of the twenty-seven-minute film, juxtaposed with the larger-thanlife IMAX movie screen, was the best kind of propaganda, designed to inspire awe. Toward the end, the narrator sums up the journey: "Today we look upon our planet from afar and feel a new tenderness for the tiny and fragile Earth."[3] And so I learned early on from documentary as well as *Star Trek* that space was a tapestry for our dreams.

By the time I was old enough to ask whether we were all allowed to go, there she was: Dr. Mae Jemison, flying to space. In a 1993 *Essence* magazine interview, Jemison told poet Nikki Giovanni, "The Third World will be the ultimate beneficiary of space technology because we're moving away from infrastructures."[4] Giovanni, who like Jemison has Alabama roots, was thrilled. This Afrofuturist techno- optimism is my favorite kind, even if as a Black feminist theoretical physicist I have become quite cynical about techno-optimism. It calls to mind bell hooks writing about Black feminist theory: "Living as we did—on the edge—we developed a particular way of seeing reality."[5] Because we live at the edge of socioeconomic structures predicated on dehumanizing us, our techno-optimism hits different. It has the potential for a different kind of politics, one where no one lives on the margins and we are all at the human center.

Jemison told Giovanni, "I wanted everyone to know that space belongs to all of us." I love this statement, though I worry about the connotation of the verb "belongs." In the context of this colonizer language, English, I often think of Adrienne Rich's poem "The Burning of Paper Instead of Children," and in particular the line "This is the oppressor's language / yet I need it to talk to you."[6] As people of the Black Atlantic, descendants of Africans who were kidnapped from their homes and forced to survive the Middle Passage and enslavement, Jemison, Giovanni, and I share a linguistic displacement. We speak the language of our ancestors' kidnappers and owners; we are socialized into their capitalist relationship to land—and now space. When Jemison says "belongs," does she mean it in the sense of "owns"? When I speak of an "ancestral heritage," do I mean something more than a capital inheritance?

Becoming Earthian

As we enter the late 2020s, the question of who owns space is one with enormous economic and political significance. Low-Earth orbit is increasingly crammed with tiny Starlink satellites launched by SpaceX, which is led by South African billionaire and Nazi saluter Elon Musk. The Black African diaspora collectively giggled in 2021 when rapper Azealia Banks referred to Musk, the child of a rich white investor in a Zambian emerald mine, as "Apartheid Clyde."[*] But, following Musk's proud Nazi salute at the January 20, 2025, presidential inauguration and his subsequent speech at a conference for Germany's far right, Nazi-adjacent AfD, it has become increasingly very not funny.

SpaceX tells us that these facilities have a humanitarian mission to provide internet to rural communities. Yet especially now that Musk's large-language model, Grok, briefly named itself "MechaHitler," I simply cannot accept that this is its only goal.[†] SpaceX's government division Starshield has been developing surveillance satellites for the National Reconnaissance Agency.[7] As a Black Jew who thinks capitalism is trash, I am worried about how the satellites may be used to surveil and eventually support efforts to round people like me up. As a founding member of the Vera C. Rubin Observatory Dark Matter Working Group, I am keenly aware that these satellites have materially damaged our ability to observe the night sky. Even if I am personally allowed to keep doing science, what if my science is foreclosed on by billionaires who blight our sky?

Musk is one of three billionaires to have launched a space company that claims to be rooted in humanitarian impulses yet looks, for all the evidence, like a power-hungry vanity project. He's even easier to pick on than Richard Branson, who seems like a reasonably nice guy but who is still a billionaire—a living representation of our broken economic system. Unlike Musk or Branson, nobody seems to like Amazon founder Jeff Bezos, who has not only gutted small businesses, threatened the survival of the book industry, and destroyed the reputation of his newspaper, the *Washington Post,* but is also a bit of a bore.

More so than the others, Musk has an extraordinary amount of undemocratically allotted power because he's not just any billionaire: He's one who spent more than the others on the current president's presidential campaign. Musk claims that he is planning to take humanity to Mars. Meanwhile, back here in reality, our global ecosystem's ability to sustain life is collapsing under the weight of centuries of white-supremacist, capitalist colonialism—the exact structures that allow Musk to be anything more than an engineer with a Twitter account. People murmur about how these billionaires are planning to escape and leave the rest of us behind on a catastrophically warmed planet. And it is easy in this context to transition from *Star Trek* fanatic to hostile, anti-space Luddite: How can we imagine leaving Earth's surface and making a livable home elsewhere when we can't even get it right here?

The idea that we can abandon Earth and not meet the same fate somewhere else is silly. Our problems travel into space with us, as exhibited by the history of exclusion from space faced by Black and disabled people, and anyone else who isn't an abled het-cis white man. And without the protection of Earth's atmosphere and the stabilizing influence of the Earth's gravitational pull, life is hard. As science studies and disability studies scholar Ashley Shew likes to remind people, we haven't even totally worked out pooping in space. Read any account by astronauts about life in orbit, and inevitably you get to amusing notes about floating poop. There are a lot of diapers involved. And for some people, life in diapers is normal and necessary. I once shared a panel with Shew where she patiently explained why colostomy-bag users are more ideal astronauts than those of us who use toilets to defecate. Conjuring the ideal spacefaring body requires a different kind of imagination.[*]

I try to listen to the teachings of the ancestors about how we move forward in these conditions. The late Nikki Giovanni was excited about going to Mars. In her collection *Make Me Rain: Poems & Prose,* Mars is a persistent refrain. That is the place that a Black child can escape to. Mars is a canvas for her Black freedom dreams. Sometimes I struggle to remember that this can be so, because our modern nationalist and capitalist space race cynically co-opts humanist visions of journeys into space. But then I think about Giovanni telling fellow Black Southerner and writer Kiese Laymon about growing okra—a staple of African and Black Atlantic diets—on Mars, and I remember, no, she is talking about a very different universe of possibilities.[†]

Black freedom dreams of space invite us to reimagine our relationship with the past in order to create spectacular new futures. In her poem "Quilting the Black-Eyed Pea (We're Going to Mars)," Giovanni declares that "the trip to Mars can only be understood through Black Americans."[8] She's referring to the Middle Passage—which actually delivered more people to Brazil and other colonies than to the United States. The ancestors who survived that journey, she imagines, know the patience required for a difficult journey and understand how to start anew after a treacherous experience. This is an uncomfortable thought for me. The distance is almost incomprehensibly enormous between a chosen journey into space and a kidnapping and compulsory transatlantic journey with insufficient food, lying in one's own waste and the waste of others, sometimes alongside people who have died or are dying. The comparison feels foul, even as I understand that she means that our ancestors made the decision to make something of their journey, to be human anyway, in all of the ways available to them. Giovanni's poem argues that NASA needs "to ask us: How did you calm your fears . . . H ow / were you able to decide you were human even when everything / said you were not . . . ?"[9]

Yet the comparison is apt in the sense that the Middle Passage produced the possibility of fantastical journeys for others; this is also the case with our current arrangement in space travel. Both Jeff Bezos and Richard Branson have lifted off from the Earth's surface and flown at least to the edge of the atmosphere, if not really to space. The economic resources that made these journeys possible find their origins in the Middle Passage and similar violent, colonial nightmares, as well as the near-sweatshop labor conditions propagated by Bezos at Amazon. What's more, the technological materials needed for spaceflight rely on the violently colonial global mining industry. In Brazil, where the real Amazon—a necessary part of our global ecosystem—is being burned to the ground, Black Brazilians known as quilombolas are displaced from their land in order to expand a spaceport in Alcântara. In Indonesia, the Indigenous Abrauw Clan of Biak Island are facing the same fate. Instead of treating the Middle Passage like a cautionary tale, our political leaders are reproducing its exploitative logics.

Stuck with the Worst of Us

This colonialism seems inescapable. So maybe I, too, want to lift off to Mars, to start over, to escape somehow. But part of the problem with being the kind of scientist I am is knowing how improbable this is—not just now but ever. After the sun, the next nearest star to Earth is Proxima Centauri. This means that the nearest planets to us outside of our solar system are Proxima Centauri b (first observed in 2016) and Proxima Centauri c (first observed in 2020). These planets are 4.2 light-years away, and because the number involved is close to zero, you might think, *Well that's not far.* But to understand what this distance entails, let's recall that a light-year is the distance light travels in the course of a year. Light, everybody knows, goes the fastest that anything can go in the universe: In a vacuum, it travels at 6.7×10^8 miles per hour, which is to say that it travels 1 million times faster than the speed limit on most American freeways. This means that to travel to Proxima Centauri in less than five years, we would need to travel a million times faster than I do on my commute. The fastest people have ever gone in space is about 25,000 miles per hour. At that speed, we could get to Proxima Centauri in 114,080 years.[*]

It's hard to go much faster than this, the speed of light notwithstanding. People necessarily go more slowly than light because the more massive an object is, the more energy required to give it speed. The 2019 and 2022 Chinese films *The Wandering Earth* and *The Wandering Earth II,* adapted from Liu Cixin's short story of the same name, imagines that when our sun enters a red-giant phase (which will genuinely happen in about 4.5 billion years), the people of Earth can collectively work together to rocket the planet to a safer location in another solar system. Though I find these films fascinating, the idea of developing the type of energy source needed to move the Earth out of orbit like that is deeply unrealistic—though ultimately *still* more likely than traveling at the speed of light. The energy required to make anything more massive than a photon (which is massless) travel at the speed of light is, in our current theories of physics, infi-nite. In other words, without a radical new understanding of space- time physics, we won't be going anywhere much farther than Mars. And our current technological capacity means that it will be a long, long while before we can sustain comfortable, habitable lifestyles there. We are apparently stuck here together, Apartheid Clyde and I.

If our species somehow managed to get ourselves to Proxima Centauri b, which is in that solar system's habitable zone, we'd also almost certainly verify what we know already from observations: It likely has no atmosphere. We would not even be in a situation where the air had the wrong composition. We'd have to populate the atmosphere from scratch, and our ability to do so would depend on getting the necessary chemicals in place, the right gravitational conditions (a massive enough planet to hold the atmosphere in place), and the right radiative environment (wherein radiation from the star wouldn't catastrophically damage the atmosphere we installed). We still don't understand our own atmosphere. It's hard to imagine we'll be building a new one anytime soon. But if we develop the capacity to do so, we should use that knowledge to salvage our home.

I hate to say "salvage," because our home has not completely burned to the ground—yet. Well, not everyone's. Global warming– induced fires have already destroyed so much. Californians like me are keenly aware of this. The entire West Coast has undergone a shift in the last few years, with "fire season" taking on a new meaning. Whole towns have been destroyed, lives lost, others permanently altered. As I drafted this book, parts of my hometown of Los Angeles burned to the ground. Meanwhile, the Global South—including the poorest and often Blackest parts of the American South—has been experiencing these kinds of violent, catastrophic transformations for a while.

The billionaire space class hangs on to their riches rather than make a potentially transformative amount of money available to public trusts that are tasked with responding to the climate disaster. They exploit Earth while dreaming of going on missions to find new lands to exploit, and they hope that other space geeks like me will join them in the delusion. But Swiss astronomer Didier Queloz was right when he said in his 2019 Nobel Prize lecture that rather than trying to resettle elsewhere in space, we should endeavor to find a way to live in equilibrium with our home planet. Queloz might seem like the best person to comment on this, since he won that Nobel Prize for his contributions to the discovery of the first of what are now nearly five thousand confirmed exoplanets, 51 Pegasi b.

51 Pegasi b is about fifty light-years away, even more impossibly out of reach than Proxima Centauri b. And it's easy to point to the impossibility of making the physics of travel work out as the reason that we have to "settle" for Earth. But we have yet to seriously consider what it would mean for us, psychologically and socially, to permanently detach from the planet that birthed us. Ultimately, we will be better positioned to succeed in our journeys far beyond our familiar star if we learn how to succeed in our journey here on Earth. Without the capacity and the will to live in good relations with our local ecosystems and each other, wherever we are, we will be on a suicide mission.

To Boldly Go

Yet for all my cynicism, I remain a dark-matter theorist who loves to share images from the Hubble Space Telescope with anyone who will look. I write a monthly column for *New Scientist* about particle physics and astrophysics specifically because I believe in humanity's powerful connection with space. Our species evolved under the night sky, and the Black feminist philosopher of science Sylvia Wynter has proclaimed us to be *Homo narrans,* a storytelling species.[10] One of our first sites of storytelling is the night sky. This is how I, the cosmologist, the cosmic storyteller, am made.

In my own work as a Black person who is a dark-matter expert, I take great pains to make clear for people that Black people are in fact not dark matter but the same kind of "normal" matter that white people are made of. I like to highlight the irony that the kind of matter that comprises both humans and stars is really a minor component of what's out there. Dark matter dominates gravitating matter. *We are the cosmic weirdos,* I love telling people. And I think Nikki Giovanni was a Martian. I don't mean she was born on Mars. But she declared her intent to go to Mars so many times that she wrote herself into the geography that I imagine for it. This reflects one of the great aspects of our traditions here in the Black Atlantic: We are always coming up with new ways to be people, and we have always known that even in terrible circumstances, the people could fly.

And so I delight in Giovanni's hypothetical to Krista Tippett in the March 17, 2016, episode of *On Being:* "Oh, what are you going to do next weekend, John? Well, Mary and I were thinking we'd just run up to this space station and have a glass of Champagne, and we'll spend the night, and we'll be back. Can you imagine sex in space?" Giovanni is asking us to imagine Black pleasure in space, to imagine something other than a capitalist catastrophe. "All my people have ever done is go forward," she goes on to tell Tippett. Maybe Black- liberation thought can get us to space in a different way. It's so easy to imagine Giovanni sitting at the bar like the one in *Star Trek: The Next Generation,* exchanging cosmic views with Whoopi Goldberg's Guinan. Two Black women philosopher poets shooting the shit at a flying space bar is a future I want to believe in.

The story goes that *Star Trek* (The Original Series) was the only show that Martin Luther King would let his children stay up late to watch. "You are reflecting what we are fighting for," he told Nichelle Nichols. Nichols went on to become an advocate for NASA, playing an active role in the program that recruited the first generation of American men and women of color who flew to space, including a physician named Mae Jemison. Nichols became one of the reasons that Guion Bluford, the first African American in space (1983), and Ronald McNair, the second (1984), pursued opportunities in the American space program.

Be clear that Black people didn't need an inspiring space role model to dream of space—those who became role models dreamed anyway. The first Black person to go to space was a Cuban revolutionary: Arnaldo Tamayo Méndez went as a Soviet Cosmonaut in 1980. And before him, in the United States there was test pilot Ed Dwight. In 1961, not long after Ed Murrow's letter to James Webb, the U.S. airman was invited to join the astronaut program. Dwight asked his mother what he should do. He recalled to NPR in 2022, "She was telling me some things about how the race could be uplifted by example and inspiration."[11] Ed Dwight's inspiration was his mother and the dream of uhuru for Black people in America.

In the end, Dwight never made it to space as a NASA astronaut, and there is no officially known record of why.[*] Dwight received extensive media attention from the Black press, and he believes it made his commander jealous. In Dwight's assessment, his otherwise all-white cohort couldn't believe that a Black pilot was the one in the spotlight. His commander got a say in who got chosen as an astronaut. In some broad sense, the minutiae of how this unfolded don't matter too much. As Black folks say among ourselves: *We* know what happened.

When she eventually lifted off, Jemison carried with her the weight of this history—and Black-ass markers of her life and world in Chicago and beyond: "An Alvin Ailey American Dance Theater poster, an Alpha Kappa Alpha banner, a flag that had flown over the Organization of African Unity, and proclamations from Chicago's DuSable Museum of African American History and the Chicago public school system," as she later told Nikki Giovanni. Jemison said that the first thing she saw from space was Chicago, but that eventually she noticed Somalia too. Seeing the globe in its totality, it was still both Black and contextualized by what her journey did and did not mean to the Black diaspora. "I'm not the first or the only African American woman who had the skills and the talent to become an astronaut. I had the opportunity. All people have produced scientists and astronomers," she told Giovanni.

This was part of Jemison's version of something all astronauts are said to experience, the overview effect: a shift in how they see the world and the universe because of their firsthand experience seeing what Carl Sagan called our "pale blue dot" from the heavens. In other words, to touch space might well be transformative—if the experience can be democratized. But this requires that we look at power differently and acknowledge its deeply uneven distribution in our globalized world. The only ethical way to see space is through practices that sanctify life rather than stand on the backs of others, which is what billionaire space cowboys are doing when they refuse to care for the environment, or to pay their workers fair wages, or to pay their fair share of taxes.

Live in the Future

We hear regularly about the apparent tension between spending on space and resource distribution here on the ground. Too many people believe that we must choose between living in better relations with our ecosystems (and each other) and going to space. People see the price tag associated with going to space—a number with a lot of zeros after it—and think we can't afford it. The reality is, NASA has gotten multiple robots to Mars on a relatively light budget. What we spend on going to space is a tiny fraction of the annual defense (or major studio filmmaking) budget alone, though much of that money does ultimately end up in the hands of defense contractors who assist in designing the launch facilities. It doesn't have to be that way, though. We can afford to do more than be space curmudgeons, and we can go to space without relying on a weaponized military-industrial complex.

I have to make this argument all the time, sometimes to myself. On the other side of it is the question of what exactly we are willing to do in exchange for the opportunity to be scientists. The fight over whether to build the Thirty Meter Telescope on Native Hawaiian land, over the objection of the kiaʻi (Native land protectors), has exposed a deep-seated colonial mindset at the heart of professional astronomy. I often think of this in terms of Bryan Kamaoli Kuwada's "We Live in the Future. Come Join Us," where he writes:

> That short-sighted model of "progress"—that we seem to be standing in the way of—hinges upon all of us, all of Hawaiʻi's people, all of the Pacific's people, all of the world's people losing connection to land, to sea, to other human beings. The less you feel these connections, the easier it is for you to be convinced that unrestricted development is the highest and best use of land.[12]

Part of what Kuwada is writing about is the colonialist, racist idea that kānaka maoli (Native Hawaiians) are backward people who, by refusing the telescope and its potential economic gains, are refusing progress and inclusion in modernity. But who is really backward here? After all, global warming is a technological development, driven by intellectual frameworks rooted in the Enlightenment.

And kanaka ways of seeing the world, understanding our interdependence on the land, on our family, invite us to reconsider and reject these imperial habits, even in the context of academic astronomy. The kiaʻi are not just fighting to protect the Mauna from further desecration but also to transition from a colonial scientific practice to an ethical science, as Keolu Fox and I argued in *The Nation*.[13] At its best, science teaches us to utilize a critical and empirical perspective on how data should be used to methodically understand the inner workings of the universe. Consider how preposterous it is to believe that only Europeans would arrive at thinking of the world and the cosmos this way. We now know from historians that many of the ideas credited to Europe have their origins in Muslim thinking that spanned the Middle East and Africa, as well as Asia and Latin America. And the evolution of these ideas had diverse interlocutors, including people of a variety of religious and cultural identities.

None of this changes the fact that science as we know it came of age with an imperial politics built on enslavement and colonialism. Even today's New Space Race, Mary-Jane Rubenstein forcefully argues, preposterously offers us "[s]alvation through imperialism."[14] But that does not mean that science can only evolve on these terms. I don't think that cruelty need be its fundamental nature. But to ensure our future looks different from the past, we must understand the past and honor the ancestors.

It can be difficult to remain hopeful about whether it is indeed possible to absorb the right lessons and truly move forward to something better. Palestinian youth activist Ahed Tamimi, who was incarcerated as a child for protesting the Israeli occupation of Palestine, reflected on the significance of cosmic connection in a 2018 interview with AJ+'s Dena Takruri. Takruri asked Tamimi what she missed most while she was in prison. Tamimi replied, "I missed gazing at the stars, at the sky, without seeing barbed wire."[15] Part of the freedom that IDF's incarceration of Tamimi stole from her was her time with the cosmos.

Tamimi is one of many Palestinians who have been robbed in this way. Scientists for Palestine is one of the organizations that provides resources for Palestinian students and scientists, including a summer physics school.

Particle physicist Nabil Iqbal, an organizer for the group, shared with me and others that every single time they tried to get permission for Gazan students to come to the West Bank for these summer schools, Israel would deny them. Even so, the students would gather in classrooms at their universities in Gaza and watch the lectures virtually, turning in their assignments using mobile phones. Those Gazan universities where the students gathered were all destroyed by spring 2024. As of this writing, I do not have a complete picture of what has happened to the students and their families.[*] As much as our political leaders like to talk about how government missions to space are for all humankind, too often Palestinians aren't who they mean. Even so, Palestinians like the aspiring astrophysicist I cited in the introduction, Wasim Said, continue to freedom dream of the night sky.

Let's Fly

As a Blackqueer person, I oscillate in and out of collective identification with "scientists." The professional scientific community that I trace my lineage through didn't even think I was a person until fairly recently. There are still scientists out there who believe that even if I am a person, I am genetically inferior. So, is their suicide mission *my* suicide mission? The premise that we are universally all in "this" together is flawed. And that too is one of Giovanni's lessons. We, the global majority, can make something our own, but we have to put the work in. To be a Black feminist physicist is to be a set of apparently contradictory frameworks trying to coexist, trying to coalesce. I want to understand; I want to reject the politics of frontier science.

Heeding Sylvia Wynter's lesson that we are a storytelling species, Black geographies theorist Katherine McKittrick says that to notice this feature is to observe "that our stories—especially our origin stories—have an impact on our neurobiological and physiological behaviors."[16] How we narrate our world and our history shapes what we become, biologically and physically. As a cosmologist, I must consider the possibility that the way we narrate the history of the universe will determine what we will become as a species—if we manage to survive. McKittrick makes the case that Black thought refuses to separate science and storytelling. And maybe that explains me, and the books I write, and my insistence on framing our universe as the best story we've ever been in conversation with or about.

McKittrick adds that "reading across our curiosities, the story and imagination are testimonies grounded in the material expression of black life. The story has physiological components. And stories make place. This means the metaphoric, allegorical, symbolic, and other devices that shape stories also move us and make place."[17] I think here McKittrick is going further than either Robert Frost or Natasha Trethewey. Now we are not simply influenced by our abiding metaphors, but they create us by becoming part of what she calls "the material expression of black life."[18] Our abiding metaphors determine how and where we live, love, make community, and reproduce. In doing so, they shape the next generations that follow on our heels. And so, we cannot fear the metaphor. "We need metaphors! Metaphors offer an (entwined material and imagined) future that has not arrived and the future we live and have already lived through," McKittrick declares.[19]

Metaphors help us map out the future by giving us a new perspective on what is past and therefore what is possible. My claim to you is that an abstraction like quantum field theory does the same. Nikki Giovanni never went to space, but her journeys to the stars helped her talk to her people about what it means to survive, to love, and sometimes thrive in the present. When trans Palestinian poet Yaffa declares "there is no / universe that / forgets what / has always been / Divine" in "Erase," I am reminded that we are the part of the universe that remembers what is strange, fascinating, and promising about it—if we choose to sanctify life and refuse erasure.[20] We need the metaphor and science. With them, we learn to imagine. And while there is danger in the techno-optimism of commercial art like the *Star Trek* franchise, there is also hope.

Six decades after Nichelle Nichols became "the first Negro astronaut," Sonequa Martin-Green became the first Black woman to lead a *Star Trek* series, *Star Trek: Discovery*. With this role, Martin-Green embodied Michael Burnham, a xenoanthropologist with specialist knowledge of physics who has trained to become a spaceship's leader. In *Discovery*'s universe, Burnham is a singular intellect. She is also a human who was raised Vulcan against the visible wishes of Vulcans in the society around her, who eventually bar her from getting a job as a scientist among them because she is human.

To help her learn about her own humanity while growing up around a species obsessed with minimizing emotion in favor of perfecting logic, Burnham's adoptive mother Amanda reads *Alice's Adventures in Wonderland* aloud to her. We see the way this literary work has shaped Burnham's extraordinary scientific intellect in season 1, episode 3, as she crawls through a duct on the spaceship *Discovery*. To help maintain her focus under extreme pressure, Burnham recites part of the first chapter of *Alice:* "The rabbit-hole went straight on like a tunnel for some way, and then dipped suddenly down, so suddenly that Alice had not a moment to think about stopping herself before she found herself falling down a very deep well."[21] In her own way, Burnham is narrating the difficult journey she has made across space, time, and racism, like many Black women (scientists) before her.

Season 2 opens with Burnham narrating a story—the epigraph of this book (go back to the beginning and take a look). At that point in the series, she is not yet a captain, a narrative choice that I understand but have at times hated and always struggle with. But when she finally does become Captain Burnham, her signature command line is, "Let's fly."[*] I am certain that the writers were thinking of *The People Could Fly* when they chose this line for her, just as they made the choice to tell a star story from Southern Africa in the opening of a season that also features a powerful meditation on spacefaring mothers and their Black daughters.[†] That story, relayed to us by a Commander Burnham who exists centuries from now, imagines a future where Black women are flying through space, exploring the unknown, carrying their ancestral knowledge and ancestral dreams out into the galaxy. Michael Burnham, a liberated Black woman fed on research *and* freedom, represents Sankofa to the future.

Maybe we can be safe in that kind of science.

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[*] True to form, this was an Instagram story that of course made the news. See, e.g., www.businessinsider.com/azealia-banks-grimes-can-finally-make-those-darn-songs-2021-9.
Go to note reference *

[†] Of course Grok was ultimately reprogrammed and no longer self-identifies this way. Large-language models, commonly known as LLMs, are not intelligent. They're algorithms that guess well. And also sometimes hallucinate and make things up.
Go to note reference †

* I highly recommend Shew's book *Against Technoableism: Rethinking Who Needs Improvement*.
Go to note reference *

† This conversation was for the 2020 Wisconsin Book Festival and can be found at https://www.youtube.com/watch?v=W8SyvGns_9w.
Go to note reference †

* If we did somehow manage to go close to the speed of light, we could take advantage of length contraction and the trip would only take five years. But in that time, the people on Earth would age more, which would introduce all sorts of social and political problems. An amazing science-fiction rendering of this scenario is captured in one of my favorite short-story collections, *I'm Waiting for You: And Other Stories,* by Korean author Kim Bo-Young, translated by Sophie Bowman and Sung Ryu.
Go to note reference *

* In 2024, Ed Dwight flew on a Bezos-owned Blue Origin spaceflight that went to the edge of the atmosphere and back.
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* Just as I began writing this book, Dr. Imad Barghouthi, who is a space scientist and professor at Al-Quds University in the West Bank in Palestine, was arrested by the Israeli Defense Forces (IDF) in the middle of the night. They came to his house and threatened to bulldoze his family's residence if he didn't go with them voluntarily. His family was not told where they were taking him. This was the third time that Professor Barghouthi had been targeted by the Zionist state. The first time he was held for over a year without conviction for "social media posts" until an international campaign applied pressure for his release in 2021. This time he was held for six months, never charged, and emerged looking almost emaciated, like a man who had been treated in dehumanizing ways by his captors.
Go to note reference *

* The first time she uses this command is at the end of season 3, episode 13. We had to wait three seasons before Michael became a captain. None of the shows featuring a white lead character has ever made their main character wait for promotion, but all three of the *Star Trek* series with a Black lead have had them in a rank below captain, even in the case of *DS9*, where Benjamin Sisko was in command of a space station. I consider Captain Carol Freeman (voiced by the brilliant Dawnn Lewis) to be the first series regular Black woman captain in franchise history, but she is not the show's lead—that is her daughter, the ultimate carefree Black girl, Ensign Beckett Mariner (voiced by the marvelous Tawny Newsome).
Go to note reference *

† For more on the source of the story, see Hollman, " 'The Sky's Things.' "
Go to note reference †

GO BACK AND GET IT

> If the eyes do not look at the sky, what else would they look at?
>
> —Igbo proverb, relayed by Damian U. Opata[1]

> Can you see the future in a starless sky?
>
> —Erin Sharkey, "An Urban Farmer's Almanac"[2]

Dear Future,

I began drafting this letter on May Day 2024, the day after the New York Police Department laid siege to the student-organized anti-genocide, pro-Palestinian liberation encampment and building occupations at Columbia University and City College of New York, while in Los Angeles, University of California Police Department and UCLA security guards watched Zionists violently assault another student-led anti-genocide, pro-liberation encampment that mostly defended itself with umbrellas. I began drafting this letter on the 209th day of Israel's genocide in Gaza.

I began work on the second draft of this book during the third week of January 2025. The genocide was supposedly in a ceasefire, but the day I wrote this sentence, IDF fired on civilians in both Palestine and Lebanon in broad daylight. Apparently, a ceasefire means still firing. Meanwhile, at home in the United States, the federal government's leaders attacked trans people with terrifying, genocidal rhetoric. I found myself practically begging strangers in public: Please stay alive. Your life is precious.

I was working on the second draft when I had a conversation with fellow particle physicist, the Nobel laureate David Gross, about how not enough people were talking about the continued threat of nuclear weapons—even as the United States has begun to increase plutonium core manufacturing for such weapons.[*] I was working on the fourth draft of this letter in late spring 2025 when ICE began aggressively hunting people in communities across the United States, including in East L.A., California, where I grew up. I felt helpless as I watched masked agents in military gear terrorize pregnant women, children, and their families. I was still working on it when Israel and the United States illegally bombed Iran, putting people I care about at risk.

I have never been more aware that we are generally on a limited clock to solve our problems. Authoritarians are rapidly and successfully accelerating their encroachment on all facets of human life regardless of identity, making it difficult to make urgently needed structural changes in order to help our species—and all other species—survive global warming, which has already begun to devastate ecosystems around the world. Coincidentally, George Orwell's novel *1984* has been selling like hotcakes.

I wept as I worked on each draft of this letter. As the California National Guard occupied Los Angeles, against the will of the people and the governor, I cried tears of pain and continued to edit sentences about the joys and pleasures of the cosmos. I am weeping in my now. I hope I am not weeping in yours. I write to you from a past that I hope feels distant to you, so that you can learn from our conditions and ensure you never find yourselves in them.

Under capitalism, it is difficult to really understand getting out of bed and participating in the world. Capitalism forecloses on other possibilities besides doing science for productive reasons. Pleasure can still fit into the picture, but only if it is profitable for *someone* that pleasure is occurring. Neoliberalism is the philosophical formation of capitalism that modern humans are most accustomed to because we are all its subjects in some way or another, even if neoliberalism isn't the organizing idea of our local or even national community. This is the power of North American, European, and other settler-colonial neo-imperialisms.

We need this lesson now, just as the generations before us did. We are in a time of what Koritha Mitchell has named “know-yourplace aggression.”[3] Around the world, people who find themselves marginalized within established nation-states are facing repressive political environments that seek to roll back any civil rights gains of earlier decades. This rise in fascism has us Black folks asking, *If they won't even treat white people well, what hope do the rest of us have?* It is terrifying, especially when we consider the overlap between these authoritarian moves and the unwillingness of the ruling class to slow the pace of global warming.

Shit is bleak. It's hard to imagine an otherwise for science besides violence, profit, and convincing rich people to let us do a little particle physics and cosmology on the side. I feel despair, and it's tempting to give in to it. But I know poet and political theorist Camonghne Felix is right when she says, “Despair is simple, it lacks complexity, it exhausts itself. At some point, you must conjure.”[4] Our own history teaches us about the power and possibility in these acts of conjure. In Vivaldi Jean-Marie's *Vodou Cosmology and the Haitian Revolution in the Enlightenment Ideals of Kant and Hegel,* we see how cosmological sensibilities helped drive an African diasporic revision of Enlightenment thought that “created the occasion for the slaves to overcome both physical and rational subjugation.”[5] Haiti's Black Jacobins and the successful Haitian Revolution ultimately inspired enslaved people across the Americas. Black liberation emerged from the freedom dreams of enslaved people who had been told not to dream at all.[*] Today, Haitians are continuing this struggle, still freedom dreaming of a world beyond colonialism.

Octavia Butler once reminded us that we must “count on the surprises”: the future isn't written until it is happening.[6] We still have the opportunity to shape it. I hope early-career scientists keep dreaming, even as fascists bang down our doors and try to set our world on fire. And as prison abolitionist Mariame Kaba has reminded us many times over the years, hope is a practice. How do you practice hope? I practiced by writing a book that I hope reminded you that the universe is bigger than the bad things happening to us, to our comrades, and to people we will never meet halfway across the world. I practiced hope by trying to write a book that will remain interesting and meaningful even after all the inhumane problems that distress us today are solved.

The universe is still out there. We choose whether we remember it or not. I bid you: Choose to remember, because the universe is where we are from, and it is our home.

The cosmos is for freedom dreamers. It is where our ancestors tried to make sense of their consciousness. Where the Muslim African ancestors looked closely at the stars in order to carefully calculate prayer times, a practice that helped them become early leaders in systematic data collection about astronomy and cosmology. The cosmos is the first site of my enslaved Black ancestors' freedom dreams. As Robert Jones Jr.'s Prophets tell a man as he self-liberates in the remarkable novel *The Prophets,* "The cosmos is on your side."[7] The cosmos was a freedom palette for the enslaved people who carved the sun and moon into their hair when they stepped off a slave ship in South America. Having survived the horrors of the Middle Passage and unsure of what terrors they would meet next, the men chose to carry the sky on their bodies.[8]

I cannot make any promises about the future—your present—except that I will fight for it, and that if our movements succeed, particle physics will be there keeping you company. Philosopher Helen De Cruz ז״ל put it so clearly when she said, "It often pays off to cultivate one's sense of awe and wonder . . . because it liberates us from existing thought patterns and ideas."[*] Wonder can be freeing. It is a kind of "education of the imagination," as José-Antonio Orosco put it.[9] When we wonder, we teach ourselves about dreaming and what kind of dreams we want to make into reality.

I hope by now I've helped you understand why I bother to think about these things, why you should bother to care, and why we should do everything we can to sustain intellectual activity that doesn't have any obvious material or financial value. I hope you feel in your gut why dark matter is one good reason to oppose financial cuts to higher education and scientific research; why students should study poetry and literature even if they plan to become engineers; why universally available, free childcare and education, including free community colleges and public universities, are essential. Our intellectual traditions are among the gifts that get passed from generation to generation, but it requires commitment to do so.

Studying the rich tradition of African Muslim science, I was struck by a description of a meteor shower by Songhay historian Mahmoud Al Kati in 1583:

> . . . after half the night had passed, stars flew around the sky as if fire had been kindled in the whole sky east, west, north and south. It became a mighty flame lighting up the earth, and people were extremely disturbed about that. It continued until after dawn.[10]

Two hundred and fifty years after Al Kati glimpsed that meteor shower, an eleven-year-old Harriet Tubman and her brother joined enslaved people across the South in witnessing the 1833 Leonid meteor storm. Tiya Miles writes in *Night Flyer* that records show enslaved people spoke of the meteor shower—which Miles calls a "celestial pageant"—with awe, comparing the visual to "sparkles."[11] Tubman thought it signaled "the end of the world had come"; that G-d's judgment day had arrived. Though enslavement continued beyond 1833—and remains in prisons to this day—Miles writes that it's worth considering whether Tubman and others saw the meteor shower as a sign. Maybe they were prefiguring June Tyson's words a century later in *Space Is the Place:* "It's after the end of the world, don't you know that yet?"

Today, I think a meteor shower would pass unnoticed by many in the United States. Certainly, there is a thriving amateur astronomy community here—one that I am a proud, card-carrying member of—which is mostly composed of people who are not professional scientists. But so many of us live in urban environments with extraordinary levels of light pollution. And the average resident is quite focused on earthly, material concerns—an understandable orientation, given the pressures of trying to survive and even thrive a little in a capitalistic society that is not organized around the survival and thriving of humans.

Ask the question what it means to be alienated from the cosmos that was once so awesome it struck fear in people's hearts. The fact that we no longer collectively look up is also a reflection of how we have departed from our ecological roots. Recurring patterns in the night sky were part of how many cultures interpreted and engaged with their local ecosystems. During June 2024, I took a one-night stargazing trip to the traditional homelands of the

Mohave, Serrano, Cahuilla, and Chemehuevi tribal nations—to Joshua Tree National Park. Surrounded by magnificent cholla cacti, I witnessed the Milky Way overhead and the myriad stars surrounding the central "milky" region, which is itself made up of gas, dust, and stars. There was so much to see that I had a hard time choosing what to look at, and I had been too busy to plan ahead like a good astrophotographer would. When we have access to a real dark night sky, there are literally so many stars that it can be hard to know what to look at. That's why looking at the night sky should be the project of a lifetime—the project of generations.

Each generation should take a part of the cosmos and deepen our understanding of it, refreshing our own humanity in the process. The figurative, the abstract, the metaphor—these are our tools too. The late Zen Buddhist leader Thích Nhất Hạnh wrote in *Being Peace,* "Life is filled with suffering, but it is also filled with many wonders, such as the blue sky, the sunshine and the eyes of a baby. To suffer is not enough. We must also be in touch with the wonders of life. They are within us and all around us, everywhere, anytime."[12] The wonder of knowing the universe is something that no one can take away from us.

And remember: Going forward does not mean forgetting the painful past. Growing up in a politically active, transnational Black and Jewish family means that I was spoon-fed this lesson practically from birth. But I was not able to consciously articulate it until my mother took me to see a screening of Haile Gerima's film *Sankofa,* which also introduced me to the concept for which it is named. *Sankofa* shows us that to go forward means to carry the memory of the ancestors with us—yes, their suffering, but also their resistance, their joy, their music, and their brilliance, which soared even in the worst possible conditions. As an Akan proverb which uses the Sankofa symbol goes: tete wɔ bi ka, tete wɔ bi kyerɛ—the ancients got something to say.

So, *nu*. I believe in, at the very least, going down swinging. And if you're reading this in the distant future, I hope it means we didn't go down at all. That it was a swing and a hit, as we baseball fans say. The moment I'm writing from is a fascist catastrophe, but if I look to the past, I see that my ancestors have faced fascist catastrophe before. How did they fight? By any means necessary. With the boogie-woogie rumble. We must resist with this knowledge—with heart, with spirit, with creativity, with curiosity, and with a refusal to comply with our own destruction. That means not just grassroots political organizing but also making art. It means looking up at the stars, just as so many of our enslaved ancestors did. It means we make our own cosmic dream boogie.

We must make the voyage home to space-time. The cosmic microwave background radiation is all around us, and it is a message arriving to us almost from the beginning, or whatever the original singularity represents. We can use what we know now, both about science and about who our peoples were, to deepen our relationship with the universe and each other. There are so many open questions about the fundamental nature of space, time, space- time, and the diversity of energetic manifestations that populate our cosmos. We experience what we think is reality, but we don't know how it is made—a sign that we are far from done. We need more time with our wonderfully queer universe. And we need to make sure that every generation has griots who have what they need to be the guardians of what we know and the creators of new stories. We can use our cosmic curiosity to put the significance of investing in caring, not killing, in proper perspective.[*] Like Nikki Giovanni told us, "The stars talk to us if we just will have enough sense to listen."[13]

To hear the message, to fully understand our space-time and be present with it, we must honor our immediate surroundings: our planet, and the region immediately beyond its atmosphere, as well as our beautiful moon. We must protect them, or we will be cut off from an essential fount of spiritual meaning and technical knowledge that has driven and inspired and nourished us for generations. We can make the voyage home, and in the process, we can save ourselves.

Dear future, may it be that we made it so.

Let's fly,
Chanda Prescod-Weinstein

יְהִי רָצוֹן מִלְּפָנֶיךָ ה' אֱ-לֹהֵינוּ וֵא-לֹהֵי אֲבוֹתֵינוּ, שֶׁתּוֹלִיכֵנוּ לְשָׁלוֹם
וְתַצְעִידֵנוּ לְשָׁלוֹם. וְתִסְמְכֵנוּ לְשָׁלוֹם. וְתַדְרִיכֵנוּ לְשָׁלוֹם. וְתַגִּיעֵנוּ
לִמְחוֹז חֶפְצֵנוּ לְחַיִּים וּלְשִׂמְחָה וּלְשָׁלוֹם וְתַצִּילֵנוּ מִכַּף כָּל אוֹיֵב
וְאוֹרֵב וְלִסְטִים וְחַיּוֹת רָעוֹת בַּדֶּרֶךְ וּמִכָּל מִינֵי פֻּרְעָנִיּוֹת הַמִּתְרַגְּשׁוֹת
לָבוֹא לָעוֹלָם וְתִשְׁלַח בְּרָכָה בְּכָל מַעֲשֵׂה יָדֵינוּ, וְתִתְּנֵנוּ לְחֵן וּלְחֶסֶד
וּלְרַחֲמִים בְּעֵינֶיךָ וּבְעֵינֵי כָל רוֹאֵינוּ וְתִשְׁמַע קוֹל תַּחֲנוּנֵינוּ. כִּי אֵ-ל
שׁוֹמֵעַ תְּפִלָּה וְתַחֲנוּן אָתָּה: בָּרוּךְ אַתָּה ה', שׁוֹמֵעַ תְּפִלָּה.

May it be Your will, Universe, our Universe and Universe of our stellar ancestors, that You lead us toward peace, guide our footsteps toward peace, and make us reach our desired destination for life, gladness, and peace. May You rescue us from the hand of every foe and ambush, from all manner of punishments that assemble to come to Earth. May You send blessing in our handiwork, and grant us grace, kindness, and mercy in Your eyes and in the eyes of all who see us. Blessed are You, Universe, which provides sufficient space-time for us to realize our prayers.

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* For more on plutonium cores and these recent changes, see: Scoles, "Behind the Scenes."
Go to note reference *

* To learn more about this, I recommend my grandfather's classic book *The Black Jacobins: Toussaint L'Ouverture and the San Domingo Revolution*.
Go to note reference *

* De Cruz, *Wonderstruck*, 16. I had hoped to send a copy of this book to De Cruz, but the world lost her to cancer on June 20, 2025. To the end, Helen used her voice to convey a sense of wonder about the world and optimism about humanity.
Go to note reference *

* "Invest in caring, not killing" is the slogan of the Global Women's Strike.
Go to note reference *

ACKNOWLEDGMENTS

Thank you to the ancestors for preparing the path.

A book like this is a superposition of the different selves who fleetingly existed during its writing. Every single day, a different version of me came to the text and added, revised, and synthesized. It's a weird process, so I am deeply thankful to have been helped along and supported in this process by an incredible community of people.

Thank you to my mom for her unflagging belief in me and her early obsession with neutrinos—always the fashionable one. Thank you to my dad for teaching me the pleasures of reading—and reading poetry especially—as a collective experience. Thank you to the rest of my family for cheering on all my writing endeavors and most especially to my parents, Auntie Roz, and Uncle Peter for reminding me why this work matters. Thank you most especially to Sharifah Zainab Williams, my sister from another mister, for drawing the figures and for bringing the best nieces into the world. I hope this book helps create the conditions where they will grow old in a thriving world.

My agent Jessica Papin has been an incredible champion, friend, and mentor. My thanks to her and the entire team at Dystel, Goderich, and Bourret LLC. It was a dream to be signed by a Pantheon Books helmed by THE Lisa Lucas. PRH leadership royally fucked that one up. IYKYK. I have had the remarkably good fortune to work with Denise Oswald, who—importantly—shares my love of horror films. I am grateful that Pantheon provided me the opportunity to work with the delightful Nicole Chung, who edits science so remarkably. My thanks to the entire PRH team, including Shanna Milkey, Rose Cronin-Jackman, Bianca Ducasse, Ciara Tomlinson, Juliane Pautrot, Demitri Papadimitropoulos, Amy Brosey, Lisa D'Agostino, Michael Collica, Tyler Comrie, Rachelle Mandik, Nicholas LoVecchio, Ian

Gibbs, and Lisa Kleinholz. I am grateful also to Maria Goldverg for her early support for this project.

I don't think this book would exist without the queer nerdery, moral support, political solidarity, and intellectual exchanges that are the foundation of my friendship with fellow theoretical physicist Brian Shuve. I probably wouldn't have gotten into so much trouble if it weren't for Sarah Tuttle, but she's also always there to help get me out of it. My comrade Lucian Walkowicz kept me honest and signifi-cantly shaped my thinking about what it means for people to be in spaces that are not Earth-bound. I have been wicked lucky to Trek through space-time with Desirae Rogers, Leen Isabel, Beth Salvia, and Galactic Barrier "Bad Frog" Rice. I am endlessly grateful to my 'Nati—Raychelle Burks, Danielle Lee, Stephani Page, and Caleph Wilson. I have been blessed by Lawrence Ware, Moya Bailey, Camonghne Felix, Elizabeth Crane, Alexis Shotwell, and Tracy Deonn, who are the best nerd thought partners. My thanks to Cappy and Elizabeth Capuano for keeping me laughing, even when I just wanted to cry. Thank you to Matthew Morrison, Daniel Harlow, Tien-Tien Yu, Seyda Ipek, Kyle Hernandez, AJ Walker, Anton Hur, John Tsou, Nick Konidaris, Sadena Thevarajah, Silva Mack, Tina Chong, Helen Kim, Meredith Schweig, the Acosta Family, Bakari Middleton, Chris Dixon, Derrick Wortes, Eman Abdelhadi, Heba Gowayed, Mike Hill, Jeremy Steffler, Ytasha Womack, Soraya Nadia McDonald, Joe Osmundson, Derek Larson, Luke Winstrom, Reuben Telushkin, and Ayinde Jean-Baptiste for holding space for all of me. To Jaleesa Trapp, Dan Wagner, Emily Spieler, Greg Wagner, Karen-Sue Taussig, Jon Kahn, Michelle Carter, and Vinny Manoharan for showing up every single year. And there are not enough thanks in the world that I can give to Iliana Konidaris for ensuring I was free to do this work.

I am a better scientist for having worked with and learned from Brian Nord. Thank you to Slavko Bogdanov for the daily nerdery and comradery, to Lisa Alexander for being in my galaxy quadrant, to Nina Metz for the commentary and moral support, and to Kiese Laymon, who has always believed in me as a writer and lit the path for so many of us. Thanks also to Okwui Onyedum and Kamala Avila-Salmon for all the Horror.

Thank you to Shawna Hollen, Elena Long, Siobhan Senier, Sheree Sharpe, and Sherri Simmons-Horton especially for being part of my New Hampshire cosmos. I am grateful to all my colleagues at University of New

Hampshire, most especially Katie Makem-Boucher and Michelle Mancini, without whom the Department of Physics and Astronomy would collapse in on itself, never to be heard from again. I am grateful also to the earlier-than-me career researchers who allowed me to collaborate with them and from whom I have learned so much: Noah Glennon, Nathan Musoke, Tony Mirasola, Nathan Rutherford, Ethan Nadler, Luna Zagorac, Gopi Mohlabeng, and Arka Banerjee. This book benefited from the holdings at the University of New Hampshire Library, which is supported by an underfunded but very mighty team.

A very special thanks to Karsten Pohl ז״ל, Jami Valentine Miller, Nadya Mason, Risa Wechsler, Anna Watts, David Kaiser, Alan Guth, Katherine McKittrick, and Priya Natarajan for warm and regular encouragement. Thank you to Marvin Avila-Salmon, andré carrington, Sean Gryb, Vijay Iyer, Matt Leifer, Franklin Leonard, Joey Neilsen, Ron Nomura, Traci Thomas, Kaitlyn Greenidge, Flip Tanedo, and Khadijah Queen for helpful conversations that shaped this book. I am grateful also to Rae Barker and John Champion for helping me with a key permission. Trekkies are the actual best.

My thanks to all of the medical professionals and body workers who help me manage my oft-troubled meat sack. My deepest gratitude to the entire team at my dentist's office, including the periodontist, the prosthodontist, the hygienist who keeps things in order, all the amazing dental technicians and assistants, and the administrative staff. This book would have been a lot harder to do without your care and thoughtfulness, including giving me the conference room to write in while I waited. To the main doc especially: Thank you for all the רְפוּאָה.

I express my heartfelt thanks to my enthusiastic *New Scientist* readers and to my editor Alison Flood and the rest of the team there. My gratitude to Maha Dakhil for being a true, principled mensch. I also thank all the creative people who have helped bring *Star Trek* to life and have been supportive of me over the years, especially Gates McFadden, Wilson Cruz, Connor Trinneer, and Anthony Rapp. Thank you to the *Star Trek: Discovery* writers room for everything, including a Black **and** Vulcan retelling of *Alice*. Thank you to Sonequa Martin-Green for bringing Michael Burnham to life. You all *did* that.

The twentieth- and twenty-first-century science discussed in this book was made possible by the generous support of the public via tax- funded projects and grants. I acknowledge and thank the program officers and scientists at government funding agencies around the world, as well as all the scientists whose work translated that financial support into knowledge. Thank you also to the entire team at FQxI for holding the line on big-picture questions in physics. Thank you to *The Baffler* for permission to publish a modified version of "Becoming Martian," which appears here as "You Are Not Safe in Science," and was originally published in the Winter 2022 issue. My thanks to the facilities and administrative staff in every place where I wrote, to the delivery drivers and to the municipal and utility workers who keep our communities clean and supplied with water and energy.

My endless thanks to my beloved, Alexis Ellison, who gave me daily reminders that even in this shitty timeline, Black joy is possible because Black love is enduring.

Last but certainly not least: Mr. Prof. Chanda, thank you for the intellectual partnership, the housework, and literally crossing oceans and continents to carry everything when my body decided it could not take any more.

NOTES

Sankofa!

1. Sègla, "The Cosmological Vision of the Yoruba-Idààcha of Benin Republic," 204.
   Go to note reference 1
2. Hughes, Rampersad, and Roessel, *The Collected Poems of Langston Hughes,* 388.
   Go to note reference 2
3. Middleton, *On the Origins of Things,* 1.
   Go to note reference 3
4. Kojo Arthur, *Cloth as Metaphor,* 274. Note that Kojo Arthur spells "sankofa" using the Twi vowel "Ɔ," which is pronounced like the "oo" in "floor."
   Go to note reference 4
5. Said, *Witness to the Hellfire of Genocide.*
   Go to note reference 5
6. Hur, *Toward Eternity,* 37.
   Go to note reference 6
7. Hountondji, *African Philosophy,* xi.
   Go to note reference 7
8. Butler, Notes on Writing.
   Go to note reference 8

Chapter One: How to Live Safely in a Science Factual Universe

1. Trethewey, “You Are Not Safe in Science.”
   Go to note reference 1
2. Frost, *Collected Prose,* 106.
   Go to note reference 2
3. Trethewey, “You Are Not Safe in Science,” 15.
   Go to note reference 3
4. Hamilton, Dillon, and Dillon, *The People Could Fly,* 166.
   Go to note reference 4
5. Trethewey, “You Are Not Safe in Science,” 25.
   Go to note reference 5
6. Trethewey, “You Are Not Safe in Science,” 21.
   Go to note reference 6
7. Barbour, *The Discovery of Dynamics,* 1.
   Go to note reference 7
8. “evolution (n.),” *Oxford English Dictionary,* September 2024, https://doi.org/10.1093/OED/3466062978.
   Go to note reference 8
9. “elaborate (adj.),” *Oxford English Dictionary,* June 2025, https://doi.org/10.1093/OED/1195263630.
   Go to note reference 9
10. Frost, *Collected Prose,* 105.
    Go to note reference 10
11. Frost and Lathem, *Poetry of Robert Frost,* 465.
    Go to note reference 11
12. Frost, *Collected Prose,* 105.
    Go to note reference 12
13. Weinberg, *Gravitation and Cosmology,* 147.
    Go to note reference 13
14. Eliot, *Collected Poems 1909–1962,* 3.
    Go to note reference 14
15. Brown, *Making Truth,* 17.
    Go to note reference 15
16. Frost, *Collected Prose,* 107.
    Go to note reference 16
17. McKittrick, *Sylvia Wynter,* 25.
    Go to note reference 17
18. Yu, *How to Live Safely in a Science Fictional Universe,* 33.
    Go to note reference 18
19. Rich, *Collected Poems,* 443.
    Go to note reference 19
20. Césaire, “Poetry and Knowledge,” 134.
    Go to note reference 20
21. Hughes, Rampersad, and Roessel, *Collected Poems of Langston Hughes,* 94.
    Go to note reference 21
22. Césaire, “Poetry and Knowledge,” 138.
    Go to note reference 22

Chapter Two: The Voyage Home

1. Rapongan, "The Eyes of the Sky."
   Go to note reference 1
2. Graham, *Later Mohist Logic, Ethics and Science,* 365.
   Go to note reference 2
3. Graham, *Later Mohist Logic, Ethics and Science,* 365.
   Go to note reference 3
4. Sagan, *Cosmos,* 4.
   Go to note reference 4
5. Green, "Challenging Epistemologies."
   Go to note reference 5
6. Huggett, *Space from Zeno to Einstein,* 4.
   Go to note reference 6
7. Huggett, *Space from Zeno to Einstein,* 5.
   Go to note reference 7
8. "Material," Wikipedia, May 31, 2025. https://en.wikipedia.org/w/index.php?title=Material&oldid=1293164564.
   Go to note reference 8
9. Poskett, *Horizons.*
   Go to note reference 9
10. Newton, *The Principia,* 416.
    Go to note reference 10
11. Newton, *The Principia,* 404.
    Go to note reference 11
12. Mozi and Johnston, *Mozi,* 415.
    Go to note reference 12
13. Mozi and Johnston, *Mozi,* 417.
    Go to note reference 13
14. Needham and Ling, *Science and Civilisation in China,* 56.
    Go to note reference 14
15. Kagame, "The Bantu Concept of Time."
    Go to note reference 15
16. Kagame, "The Bantu Concept of Time," 4.
    Go to note reference 16
17. Aja, "Time and Space in African (Igbo) Thought."
    Go to note reference 17
18. Césaire, "Poetry and Knowledge," 144.
    Go to note reference 18
19. Iniguez, *Mexicans on the Moon,* 65.
    Go to note reference 19

Chapter Three: Space-Time Is the Place

1. Quine, “The Scope and Language of Science,” 14.
   Go to note reference 1
2. Hobson, Efstathiou, and Lasenby, *General Relativity,* 148.
   Go to note reference 2
3. Prescod-Weinstein, *Disordered Cosmos,* 56.
   Go to note reference 3

Chapter Four: The Cosmic Origins of the 808

1. Lee and Kirby, *Amazing Fantasy. No. 15*.
   [Go to note reference 1]
2. Laymon, *Long Division,* 5.
   [Go to note reference 2]
3. Guth, *Inflationary Universe,* 16.
   [Go to note reference 3]
4. Smith, *Life on Mars,* 13.
   [Go to note reference 4]
5. Sagan, *Cosmic Connection,* 189–190.
   [Go to note reference 5]

Chapter Five: Beyond a Cosmic Boundary

1. James, *Beyond a Boundary,* 198.
   [Go to note reference 1]
2. Du Châtelet, *Selected Philosophical and Scientific Writings,* 121.
   [Go to note reference 2]
3. Bursten, "Function of Boundary Conditions in the Physical Sciences," 235.
   [Go to note reference 3]
4. Paksi, "Concept of Boundary Conditions," 9.
   [Go to note reference 4]
5. Hawking, Ellis, and Ashtekar, *Large Scale Structure of Space-Time,* 1.
   [Go to note reference 5]
6. Hawking, Ellis, and Ashtekar, *Large Scale Structure of Space-Time,* xix.
   [Go to note reference 6]
7. Hawking, Ellis, and Ashtekar, *Large Scale Structure of Space-Time,* 3.
   [Go to note reference 7]

Chapter Six: Baby's First Field Theory

1. Shankar, *Fundamentals of Physics II,* 16.
   Go to note reference 1
2. Faraday, *Faraday's Diary,* 331.
   Go to note reference 2
3. "field (n.1)," *Oxford English Dictionary,* June 2025, https://doi.org/10.1093/OED/1125899776.
   Go to note reference 3
4. Maxwell, "A Dynamical Theory of the Electromagnetic Field," 460.
   Go to note reference 4
5. Shankar, *Fundamentals of Physics II,* 264.
   Go to note reference 5
6. Einstein et al., *Principle of Relativity,* 37.
   Go to note reference 6

Chapter Seven: The Book of Nonsense

1. Lear and Noakes, *Complete Nonsense and Other Verse,* 163.
   Go to note reference 1
2. Blackmon, "Quantum Distributions for Sarah Baartman."
   Go to note reference 2
3. Dirac, *Principles of Quantum Mechanics*, 3.
   Go to note reference 3

Chapter Eight: The Quantum Turn

1. Carroll and Tenniel, *Annotated Alice,* 80.
   [Go to note reference 1]
2. Bauer, "The Stern–Gerlach Experiment."
   [Go to note reference 2]
3. Popper, *Logic of Scientific Discovery*.
   [Go to note reference 3]
4. In the most Wonderland kind of way, the only way to describe the results of experiments like Stern–Gerlach is to use wave functions that have complex numbers in them. To mathematically describe the state of a quantum object, we cannot use the vectors made of real numbers that we used earlier to follow the trajectory of a baseball. The calculational techniques involved are governed by rules guaranteeing that things we might actually observe, like the position of an object, are always given by what are called "real" numbers. But along the way, we may need to use objects called "complex numbers" in our calculations.

   Complex numbers are another mathematical tool available for describing a combination of quantum states. Their foundation is the square root of −1—an imaginary number, represented by *i*. It's called an imaginary number because it is not "real" like the numbers we use to count our fingers and toes. Descartes actually gave real numbers the name "real" in order to distinguish them from this concept of an imaginary number, which can be thought of as an extension of real numbers that add in the capacity to deal with multiples of the square root of −1, which is denoted by the imaginary number *i*.

   Don't panic! Yes, I just walked you into a bit of math: You can do this. It's also okay to briefly panic—feel your feelings! But your feelings are not in charge, and you can do this. Remember that 2 times 2 equals 4? As in, 2, multiplied by itself, gives 4. This is a square—when a number is multiplied by itself. The reverse of this process is the square root, as in 2 is said to be the square root of 4. Every real number has a square root, although not all of them are pretty. For example, the number that multiplies by itself to give 2 is irrational—it cannot be expressed using non-decimal numbers alone—and has an approximate value of 1.4142. (Try it in your phone calculator or favorite search engine: Multiply 1.4142 by 1.4142. You will get a number that is almost exactly 2, a result that gets more accurate with increasingly accurate square root values.) The simplest square root is 1: It's the square root of itself.

   Perhaps you're getting the hang of square roots, and maybe you already know something about negative numbers. These are numbers that literally have a minus sign in front of them. And when we do arithmetic, that's exactly how they behave. 2 + −2 is the same as 2 − 2. Both are equal to 0. Now, what's the square root of −1? Is it −1? No! If you multiply −1 by −1, you get 1, and we know the square root of 1 is 1. The symmetry is broken. In order to create a square root for −1, we define the symbol *i* as its square root. By definition. There's no convincing you, you just have to accept it.
   [Go to note reference 4]
5. *Star Trek: Discovery,* Season 1, Episode 3, circa 44:45.
   [Go to note reference 5]
6. Moses and Cobb, *Radical Equations,* 14–15.
   [Go to note reference 6]

Chapter Nine: TRAP Phenomenology

1. Carroll, *Annotated Alice,* 236.
   Go to note reference 1
2. Shaw, *Trap History,* 12.
   Go to note reference 2
3. Kearse, "Childish Gambino."
   Go to note reference 3
4. Kragh, *Higher Speculations,* 11.
   Go to note reference 4
5. Descartes, *Philosophical Writings* 3, 38.
   Go to note reference 5
6. Poskett, *Horizons,* 67.
   Go to note reference 6
7. Martin, *Solid State Insurrection,* 34.
   Go to note reference 7
8. Dirac, *Principles,* 3.
   Go to note reference 8
9. Bell, *Foundations of Quantum Mechanics,* 99.
   Go to note reference 9
10. Bell, *Foundations of Quantum Mechanics,* 100.
    Go to note reference 10
11. Ballentine, *Quantum Mechanics,* 42.
    Go to note reference 11
12. Ballentine, *Quantum Mechanics,* 47.
    Go to note reference 12
13. Dirac, *Principles,* 10.
    Go to note reference 13
14. Barad, *Meeting the Universe Halfway,* 23.
    Go to note reference 14
15. Einstein, Podolsky, and Rosen, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" 777.
    Go to note reference 15
16. Rauch et al., "Cosmic Bell Test."
    Go to note reference 16
17. Barad, *Meeting the Universe Halfway*.
    Go to note reference 17
18. Bell, *Foundations of Quantum Mechanics,* 208.
    Go to note reference 18
19. Catani et al., "Why Interference Phenomena Do Not Capture the Essence of Quantum Theory," 5.
    Go to note reference 19

Chapter Ten: Quantum Sankofa

1. Carroll, *The Annotated Alice,* 11.
   Go to note reference 1
2. Melville, *Moby-Dick,* 272.
   Go to note reference 2
3. Eliot, *Collected Poems 1909–1962,* 175.
   Go to note reference 3
4. Brumfiel, "Researchers Say Time Is an Illusion."
   Go to note reference 4
5. Chakrabarty, *Provincializing Europe,* 73.
   Go to note reference 5
6. Newton, *Principia,* 408.
   Go to note reference 6
7. Venning, "Time's Arrow."
   Go to note reference 7
8. Barbour, *Janus Point,* 19. See also: Gomes, Gryb, and Koslowski, "Einstein Gravity as a 3D Conformally Invariant Theory," for a novel quantum gravity model that touches on these ideas.
   Go to note reference 8

Part III

1. Carroll, *Annotated Alice,* 22.
   Go to note reference 1

Chapter Eleven: The Photon Collectors

1. Somerville, *On the Connection of the Physical Sciences,* 1.
   Go to note reference 1
2. Matthews, *Simulacra,* 34.
   Go to note reference 2
3. Peebles, *Cosmology's Century,* 84.
   Go to note reference 3
4. Weinberg, *Quantum Theory of Fields 1,* 15.
   Go to note reference 4

Chapter Twelve: You Are an Abstract Contraption Made of Nothing

1. Carroll, *Annotated Alice,* 167.
   Go to note reference 1
2. Newton, *Principia,* 408.
   Go to note reference 2
3. Spinoza, *Spinoza's Ethics,* 14.
   Go to note reference 3
4. Redhead, "A Philosopher Tackles Quantum Field Theory."
   Go to note reference 4
5. Césaire, "Poetry and Knowledge," 140.
   Go to note reference 5

Chapter Thirteen: The Vacuum Will Tear Us Apart

1. Mickens, "Titus Pankey and the Supernova Ia Lightcurve."
   Go to note reference 1
2. Prescod-Weinstein, "Cosmic Acceleration as Quantum Gravity Phenomenology."
   Go to note reference 2
3. Poulin et al., "Early Dark Energy Can Resolve the Hubble Tension."
   Go to note reference 3
4. Falk, "The 'Least Crazy' Idea."
   Go to note reference 4

Chapter Fourteen: All That We May Never See

1. Peebles, *Cosmology's Century,* 84.
   Go to note reference 1
2. See the chapter "Black People Are Luminous Matter," in Prescod-Weinstein, *Disordered Cosmos*.
   Go to note reference 2
3. Glennon and Prescod-Weinstein, "Modifying PyUltraLight to Model Scalar Dark Matter with Self-Interactions"; Glennon et al., "Tidal Disruption of Solitons in Self-Interacting Ultralight Axion Dark Matter"; Glennon et al., "Dynamical Friction in Self-Interacting Ultralight Dark Matter"; Glennon, Musoke, and Prescod-Weinstein, "Simulations of Multi-Field Ultralight Axion-like Dark Matter."
   Go to note reference 3
4. Carroll, *Annotated Alice,* 174.
   Go to note reference 4

Chapter Fifteen: The Ultimate Tool for Laying Edges

1. Milne, *When We Were Very Young,* 30.
   Go to note reference 1
2. Miller, *Tender the River,* 24.
   Go to note reference 2
3. Hammonds, “Black (W)Holes and the Geometry of Black Female Sexuality”; Prescod-Weinstein, “The Cosmos Is a Black Aesthetic.”
   Go to note reference 3

Chapter Sixteen: U.N.I.T.Y.

1. Hawking, *Illustrated A Brief History of Time,* 11.
   Go to note reference 1
2. Rovelli, "Notes for a Brief History of Quantum Gravity."
   Go to note reference 2
3. Mozi and Johnston, *Mozi,* 475.
   Go to note reference 3
4. Smolin, *Three Roads to Quantum Gravity*.
   Go to note reference 4
5. Hawking and Hertog, "Populating the Landscape."
   Go to note reference 5
6. Faux and Gates Jr., "Adinkras."
   Go to note reference 6

Chapter Seventeen: Cosmic Energy

1. Wilson, *Research Is Ceremony,* 90.
   Go to note reference 1
2. Graves, *Milford Graves Full Mantis,* roughly at 16:40.
   Go to note reference 2
3. "energy (n.)," *Merriam-Webster Online,* June 14, 2025. www.merriam-webster.com/dictionary/energy.
   Go to note reference 3
4. Rutherford et al., "Constraining Bosonic Asymmetric Dark Matter with Neutron Star Mass-Radius Measurements"; Rutherford, Prescod-Weinstein, and Watts, "Probing Fermionic Asymmetric Dark Matter Cores Using Global Neutron Star Properties."
   Go to note reference 4
5. Côté et al., "The Origin of R-Process Elements in the Milky Way."
   Go to note reference 5
6. Riofrancos, *Resource Radicals*.
   Go to note reference 6
7. "Democratic Republic of the Congo: Economy." Global Edge, Accessed June 19, 2025. https://globaledge.msu.edu/countries/democratic-republic-of-the-congo/economy; Ojewale, "What Coltan Mining in the DRC Costs People and the Environment."
   Go to note reference 7
8. McKean, *Disorienting Neoliberalism*.
   Go to note reference 8
9. Hecht, *Residual Governance*.
   Go to note reference 9
10. Arboleda, *Planetary Mine,* 251.
    Go to note reference 10
11. Williams and Uzeyman, *Neptune Frost,* 54:46.
    Go to note reference 11
12. Williams and Uzeyman, *Neptune Frost,* 50:36.
    Go to note reference 12

Chapter Eighteen: You Are Not Safe in Science

1. *Ebony,* “A New Star in the TV Heavens.”
   Go to note reference 1
2. Logsdon, “John F. Kennedy and the ‘Right Stuff,’ ” 12.
   Go to note reference 2
3. Freeman and MacGillivray, *To Fly!,* 25:06.
   Go to note reference 3
4. Giovanni, “Shooting for the Moon—Scientist and Astronaut Mae C. Jemison.”
   Go to note reference 4
5. hooks, *Feminist Theory,* xviii.
   Go to note reference 5
6. Rich, *Collected Poems,* 304.
   Go to note reference 6
7. Trevithick and Rogoway, “If SpaceX’s Secret Constellation Is What We Think It Is, It’s Game Changing.”
   Go to note reference 7
8. Giovanni, *Quilting the Black-Eyed Pea,* 3.
   Go to note reference 8
9. Giovanni, *Quilting the Black-Eyed Pea,* 4.
   Go to note reference 9
10. McKittrick, *Sylvia Wynter,* 25.
    Go to note reference 10
11. Hazel, “Ed Dwight Was in Line to Be the First Black Astronaut. History Had Other Ideas.”
    Go to note reference 11
12. Kuwada, “We Live in the Future.”
    Go to note reference 12
13. Fox and Prescod-Weinstein, “The Fight for Mauna Kea Is a Fight Against Colonial Science.”
    Go to note reference 13
14. Rubenstein, *Astrotopia,* 4.
    Go to note reference 14
15. Tamimi, “They Could Kill Me at Any Time.”
    Go to note reference 15
16. McKittrick, *Dear Science and Other Stories,* 9.
    Go to note reference 16
17. McKittrick, *Dear Science and Other Stories,* 9.
    Go to note reference 17
18. McKittrick, *Dear Science and Other Stories,* 9.
    Go to note reference 18
19. McKittrick, *Dear Science and Other Stories,* 11.
    Go to note reference 19
20. Yaffa AS, *Sage*, 40.
    Go to note reference 20
21. Carroll, *The Annotated Alice: 150th Anniversary Deluxe Edition,* 12.
    Go to note reference 21

Go Back and Get It

1. Opata, “Cultural Astronomy in the Lore and Literature of Africa,” 217.

Go to note reference 1

2. Sharkey, *Darker Wilderness,* 118.

Go to note reference 2

3. Mitchell, "Identifying White Mediocrity and Know-Your-Place Aggression."

Go to note reference 3

4. Felix, *Let the Poets Govern,* 170.

Go to note reference 3

5. Jean-Marie, *Vodou Cosmology and the Haitian Revolution in the Enlightenment Ideals of Kant and Hegel,* 5.

Go to note reference 5

6. Butler, "A Few Rules for Predicting the Future."

Go to note reference 6

7. Jones Jr., *Prophets,* 336.

Go to note reference 7

8. Mintz and Price, *The Birth of African-American Culture,* 48.

Go to note reference 8

9. Orosco, *Star Trek's Philosophy of Peace and Justice,* 10.

Go to note reference 9

10. Medupe et al., "The Timbuktu Astronomy Project: A Scientific Exploration of the Secrets of the Archives of Timbuktu," 182.

Go to note reference 10

11. Miles, *Night Flyer,* 65.

Go to note reference 11

12. Thích Nhất Hạnh, *Being Peace,* xiv.

Go to note reference 12

13. Giovanni, "Craft," 164.

Go to note reference 13

BIBLIOGRAPHY AND RECOMMENDED READING

Below you will find a complete list of all the texts I mentioned or directly cited in *The Edge of Space-Time,* along with a few recommendations of where to read further. I used library holdings, which are actively managed by librarians, to write this book. **Libraries are fucking awesome**, and librarians and archivists are people who do what they do because they love books and information and care about sharing them with people. If you'd like to follow up on the reading by looking at any of these books or articles, remember your local library is there to help you do that! As of this writing, federal funding for libraries is under attack, and politicians around the country are trying to implement book bans that would control what kind of content libraries can carry. They are specifically targeting books that touch on people of color and LGBTQ+ people—and most especially people who are both. Make sure you are vocal in your community about the importance of libraries and the right of everyone—regardless of age—to read books of their choosing. Our Prince said, Black books, like Black people, matter. To which I add: Queer books, like queer people, are precious. And Blackqueer people like me are going to keep writing.

Recommended Books

fshordi, Niayesh, and Phil Halper. *Battle of the Big Bang: The New Tales of Our Cosmic Origins*. University of Chicago Press, 2025.

guirre, Anthony. *Cosmological Koans*. W. W. Norton & Company, 2019.

arroll, Sean M. *The Biggest Ideas in the Universe: Space, Time, and Motion*. Dutton, 2022.

________. *The Biggest Ideas in the Universe: Quanta and Fields*. Dutton, 2024.

hapman, Emma Olivia. *First Light: Switching on Stars at the Dawn of Time*. Blooms-bury Sigma Series. Zed Books, 2021. https://doi.org/10.5040/9781472962911.

ickinson, Terrence, and Alan Dyer. *The Backyard Astronomers Guide.* 4 ed. Firefly Books, 2021.

ine, Michael. *This Way to the Universe: A Theoretical Physicist's Journey to the Edge of Reality*. Dutton, 2022.

ohnson, Clifford V. *The Dialogues: Conversations About the Nature of the Universe*. MIT Press, 2018.

egault, Thierry. *Astrophotography.* Rocky Nook, 2014.

ack, Katie. *The End of Everything (Astrophysically Speaking)*. Scribner, 2021.

oskvitch, Katia. *Neutron Stars: The Quest to Understand the Zombies of the Cosmos*. Harvard University Press, 2020.

atarajan, Priyamvada. *Mapping the Heavens: The Radical Scientific Ideas That Reveal the Cosmos*. Yale University Press, 2016.

trassler, Matt. *Waves in an Impossible Sea: How Everyday Life Emerges from the Cosmic Ocean*. Basic Books, 2024.

ulpen, Ivo van. *How to Find a Higgs Boson—and Other Big Mysteries in the World of the Very Small.* Translated by David McKay. Yale University Press, 2020.

Bibliography

bu Mezied, Asmaa. “Lost Identity: The Tale of Peasantry and Nature.” In *Light in Gaza: Writings Born of Fire,* edited by Jehad Abusalim, Jennifer Bing-Canar, and Michael Lotze. Haymarket Books, 2022.

hmed, Sara. *Queer Phenomenology: Orientations, Objects, Others*. Duke University Press, 2006.

hn, Eun-Joo. “Re-Remembering Benjamin Whisoh Lee, Promoter of Gauge Theories.” *Physics Today* 78, no. 6 (June 1, 2025): 36–43.

ja, Egbeke. “Time and Space in African (Igbo) Thought.” *Philosophy in the Contemporary World* 1, no. 1 (February 1, 1994): 1–8.

nanthaswamy, Anil. *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality*. Dutton, 2018.

rboleda, Martín. *Planetary Mine: Territories of Extraction Under Late Capitalism*. Verso, 2020.

rthur, G. F. Kojo. *Cloth as Metaphor: (Re)Reading the Adinkra Cloth: Symbols of the Akan of Ghana, 2nd Edition*. iUniverse, 2017.

usten, Jane. *The Annotated Mansfield Park*. Knopf Doubleday Publishing Group, 2017.

ailey, Moya. *Misogynoir Transformed: Black Women’s Digital Resistance*. Intersections. New York University Press, 2022.

allentine, Leslie E. *Quantum Mechanics: A Modern Development*. Reprinted. Singapore: World Scientific, 2006.

arad, Karen Michelle. *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning*. Duke University Press, 2007.

arber, Regina. “In Honor of ‘Star Trek: Strange New Worlds’ Season 2, a Tour of the Physics.” Produced by Berly McCoy, edited by Rebecca Ramirez. *NPR Short Wave*, June 19, 2023. Podcast, Mp3. 16:45, www.npr.org/transcripts/1182450107.

arbour, Julian B. *The Discovery of Dynamics: A Study from a Machian Point of View of the Discovery and the Structure of Dynamical Theories*. Oxford University Press, 2001.

________. *The Janus Point: A New Theory of Time*. Basic Books, 2020.

auer, Martin. “The Stern–Gerlach Experiment, Translation of: ‘Der Experimentelle Nachweis der Richtungsquantelung im Magnetfeld.’ ” arXiv, January 26, 2023, https://arxiv.org/abs/2301.11343v1.

ecker, Adam. *What Is Real?: The Unfinished Quest for the Meaning of Quantum Physics*. Basic Books, 2019.

ell, John S. *John S. Bell on the Foundations of Quantum Mechanics,* edited by Mary Bell, Kurt Gottfried, and Martinus Veltman. World Scientific, 2001.

enjamin, Ruha. *Imagination: A Manifesto*. W. W. Norton & Company, 2024.

lackmon, Lena. “Quantum Distributions for Sarah Baartman.” *The Offing,* June 28, 2018, theoffingmag.com/backoftheenvelope/quantum-distributions-sarah-baartman/.

rown, Theodore L. *Making Truth: Metaphor in Science*. University of Illinois Press, 2008.

rumfiel, Geoff. “Researchers Say Time Is an Illusion. So Why Are We All Obsessed with It?” NPR, December 16, 2022, www.npr.org/2022/12/16/1139780043/what-is-time-physics-atomic-clocks-society.

ursten, Julia R. S. “The Function of Boundary Conditions in the Physical Sciences.” *Philosophy of Science* 88, no. 2 (April 1, 2021): 234–257.

utler, Octavia. “A Few Rules for Predicting the Future.” *Essence Magazine,* May 2000.

utler, Octavia E. *Parable of the Talents*. Paperback reissue. Grand Central Publishing, 2019.

________. *A Few Rules for Predicting the Future: An Essay*. Chronicle Books, 2024.

________. Notes on Writing, “I Am a Bestselling Writer . . .” Huntington Library, Art Collections, and Botanical Gardens. 1988.

utler, Octavia E., and N. K. Jemisin. *Parable of the Sower*. Paperback reissue. Grand Central Publishing, 2019.

arroll, Lewis. *Alice in Wonderland: A Norton Critical Edition,* edited by Donald J. Gray. W. W. Norton & Company, 2024.

________. *The Annotated Alice: 150th Anniversary Deluxe Edition,* edited by Martin Gardner and Mark Burstein. W. W. Norton & Company, 2015.

atani, Lorenzo, Matthew Leifer, David Schmid, and Robert W. Spekkens. “Why Interference Phenomena Do Not Capture the Essence of Quantum Theory.” arXiv, July 24, 2022, http://arxiv.org/abs/2111.13727.

ésaire, Aimé. “Poetry and Knowledge,” in *Refusal of the Shadow: Surrealism and the Caribbean,* edited by Michael Richardson and Krzysztof Fijałkowski. Verso, 1996.

hakrabarty, Dipesh. *Provincializing Europe: Postcolonial Thought and Historical Difference*. Princeton Studies in Culture / Power / History, Princeton University Press, 2007.

hung, Nicole. *All You Can Ever Know: A Memoir*. Catapult, 2019.

ôté, Benoit, Chris L. Fryer, Krzysztof Belczynski, Oleg Korobkin, Martyna Chruślińska, Nicole Vassh, Matthew R. Mumpower, et al. “The Origin of R-Process Elements in the Milky Way.” *The Astrophysical Journal* 855, no. 2 (March 2018): 99.

e Cruz, Helen. *Wonderstruck: How Wonder and Awe Shape the Way We Think.* Princeton University Press, 2024.

escartes, René. *The Philosophical Writings of Descartes, 3: The Correspondence*. Cambridge University Press, 1997.

irac, Paul A. M. *The Principles of Quantum Mechanics*. 4. ed. (rev.), Repr. International Series of Monographs on Physics 27. Clarendon Press, 2010.

u Châtelet, Gabrielle Émilie Le Tonnelier de Breteuil, and Judith P. Zinsser. *Selected Philosophical and Scientific Writings*. University of Chicago Press, 2009.

bony. “A New Star in the TV Heavens.” January 1967.

instein, Albert, Hendrik A. Lorentz, Hermann Minkowski, and Hermann Weyl. *The Principle of Relativity: A Collection of Orig. Memoirs on the Special and General Theory of Relativity*. Dover, 1970.

instein, A., B. Podolsky, and N. Rosen. “Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?” *Physical Review* 47, no. 10 (May 15, 1935): 777–780.

liot, T. S. *Collected Poems 1909–1962*. Harcourt Brace Jovanovich, 1991.

nde, Michael. *The Neverending Story,* translated by Ralph Manheim. Penguin Group (USA), 2005.

alk, Dan. “The ‘Least Crazy’ Idea: Early Dark Energy Could Solve a Cosmological Conundrum.” *Astronomy Magazine,* October 5, 2023, www.astronomy.com/science/the-least-crazy-idea-early-dark-energy-could-solve-a-cosmological-conundrum/.

araday, Michael. *Faraday’s Diary: Being the Various Philosophical Notes of Experimental Investigation. Vol. 4: Nov. 12, 1839–June 26, 1847,* edited by Thomas Martin. Second edition with integrated index. HR Direct, 2008.

aux, Michael, and S. J. Gates Jr. "Adinkras: A Graphical Technology for Super-symmetric Representation Theory." arXiv.org, August 2, 2004, https://arxiv.org/abs/hep-th/0408004.

elix, Camonghne. *Let the Poets Govern: A Declaration of Freedom*. One World, 2026.

ox, Keolu, and Chanda Prescod-Weinstein. "The Fight for Mauna Kea Is a Fight Against Colonial Science," *The Nation,* July 24, 2019, www.thenation.com/article/archive/mauna-kea-tmt-colonial-science/.

reeman, Jim, and Greg MacGillivray, directors. *To Fly!,* Conoco, 1976. 27 min.

rost, Robert. *The Collected Prose of Robert Frost,* edited by Mark Richardson. Belknap Press, 2009.

rost, Robert, and Edward Connery Lathem. *The Poetry of Robert Frost: The Collected Poems*. Holt, 2002.

aillard, Mary. *A Singularly Unfeminine Profession: One Woman's Journey in Physics*. World Scientific, 2015.

ates, Delilah Elizabeth Abney. "Observational Electromagnetic Signatures of Spinning Black Holes." PhD Thesis, Harvard University, 2021, https://dash.harvard.edu/handle/1/37368469.

iovanni, Nikki. "Craft." In *How We Do It: Black Writers on Craft, Practice, and Skill,* edited by Jericho Brown. Amistad, 2023.

________. *Quilting the Black-Eyed Pea: Poems and Not Quite Poems*. Harper Perennial, 2011.

________. "Shooting for the Moon—Scientist and Astronaut Mae C. Jemison." *Essence Magazine,* April 1993.

lennon, Noah, Nathan Musoke, Ethan O. Nadler, Chanda Prescod-Weinstein, and Risa H. Wechsler. "Dynamical Friction in Self-Interacting Ultralight Dark Matter." *Physical Review D* 109, no. 6 (March 1, 2024): 063501, https://doi.org/10.1103/physrevd.109.063501.

lennon, Noah, Nathan Musoke, and Chanda Prescod-Weinstein. "Simulations of Multi-Field Ultralight Axion-like Dark Matter." *Physical Review D* 107, no. 6 (March 15, 2023): 063520, https://doi.org/10.1103/PhysRevD.107.063520.

lennon, Noah, Ethan O. Nadler, Nathan Musoke, Arka Banerjee, Chanda Prescod-Weinstein, and Risa H. Wechsler. "Tidal Disruption of Solitons in Self-Interacting Ultralight Axion Dark Matter." *Physical Review D* 105, no. 123540 (June 30, 2022), https://journals.aps.org/prd/abstract/10.1103/PhysRevD.105.123540.

lennon, Noah, and Chanda Prescod-Weinstein. "Modifying PyUltraLight to Model Scalar Dark Matter with Self-Interactions." *Physical Review D* 104, no. 8 (October 20, 2021): 083532, https://doi.org/10.1103/PhysRevD.104.083532.

omes, Henrique, Sean Gryb, and Tim Koslowski. "Einstein Gravity as a 3D Con-formally Invariant Theory." *Classical and Quantum Gravity* 28, no. 4 (February 21, 2011): 045005.

onick, Larry, and Arthur Huffman. *The Cartoon Guide to Physics*. Collins Reference, 2008.

raham, Angus C. *Later Mohist Logic, Ethics and Science*. Chinese University Press, 2003.

reen, Lesley J. F. "Challenging Epistemologies: Exploring Knowledge Practices in Palikur Astronomy." *Futures* 41, no. 1 (February 1, 2009): 41–52. Special issue "Futures of Indigenous Knowledges."

uth, Alan H. *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins*. Addison-Wesley Longman, 2000.

aley, Alex. *Roots: The Saga of an American Family*. Da Capo Press, 2014.

amilton, Virginia, Leo Dillon, and Diane Dillon, eds. *The People Could Fly: American Black Folktales*. Knopf, 1993.

ammonds, Evelynn. "Black (W)Holes and the Geometry of Black Female Sexuality." *Differences* 6, no. 2–3 (July 1, 1994): 126–145.

ạnh, Thích Nhất. *Being Peace*. Parallax Press, 2020.

arlow, Daniel. "Black Holes in Quantum Gravity." arXiv, April 19, 2023, http://arxiv.org/abs/2304.10367.

Iawking, Stephen W. *The Illustrated A Brief History of Time*. Updated and Expanded Edition. Bantam Books, 1996.

Iawking, Stephen W., George F. R. Ellis, and Abhay Ashtekar. *The Large Scale Structure of Space-Time*. 50th Anniversary Edition. Cambridge University Press, 2023.

Iawking, Stephen W., and Thomas Hertog. “Populating the Landscape: A Top- down Approach.” *Physical Review D* 73, no. 12 (June 23, 2006): 123527, https://doi.org/10.1103/PhysRevD.73.123527.

Iazel, Mycah. “Ed Dwight Was in Line to Be the First Black Astronaut. History Had Other Ideas.” NPR, July 5, 2022, www.npr.org/2022/07/05/1109678316/edward-dwight-space-race-nasa-astronaut-moon.

Iecht, Gabrielle. *Residual Governance: How South Africa Foretells Planetary Futures*. Duke University Press, 2023.

Iertog, Thomas. *On the Origin of Time: Stephen Hawking's Final Theory*. Bantam, 2023.

Iobson, Michael P., George Efstathiou, and Anthony Lasenby. *General Relativity: An Introduction for Physicists*. Cambridge University Press, 2013.

Iollman, J. C. “ ‘The Sky's Things’, |xam Bushman ‘Astrological Mythology’ as Recorded in the Bleek and Lloyd Manuscripts.” *African Skies* 11 (July 2007): 8.

ooks, bell. *Feminist Theory: From Margin to Center*. Routledge, 2015.

Iountondji, Paulin J. *African Philosophy: Myth and Reality*. Indiana University Press, 1996.

Iuggett, Nick, ed. *Space from Zeno to Einstein: Classic Readings with a Contemporary Commentary*. MIT Press, 1999.

Iughes, Langston, Arnold Rampersad, and David E. Roessel. *The Collected Poems of Langston Hughes*. Vintage Books, 1995.

Iur, Anton. *Toward Eternity*. HarperCollins Publishers, 2024.

niguez, Pedro. *Mexicans on the Moon: Speculative Poetry from a Possible Future*. Space Cowboy Books, 2024.

sler, Jedidah C. “In Like a Lamb, Out Like a Lion: Probing the Disk-Jet Connection in Fermi Gamma-Ray Bright Blazars.” PhD Thesis, Yale University, 2014, www.proquest.com/docview/1541890867.

ackson, Sarah J. *Second Sight: How the Wonder and Vision of Black Mediamakers Push America Toward Freedom.* Mariner Books, 2026.

ean-Marie Vivaldi. *Vodou Cosmology and the Haitian Revolution in the Enlightenment Ideals of Kant and Hegel*. University of the West Indies Press, 2018.

ames, C.L.R. *Beyond a Boundary: 50th Anniversary Edition*. Duke University Press, 2013.

________. *The Black Jacobins: Toussaint l'Ouverture and the San Domingo Revolution*. Vintage Books, 1989.

ones Jr., Robert. *The Prophets*. G. P. Putnam's Sons, 2021.

agame, Alexis. “The Bantu Concept of Time.” Translated by Jean-Paul Martinon. “The Development of Philosophy in the Contemporary World: ‘Time and History in World Cultures.’ ” United Nations Educational, Scientific and Cultural Organization, 1970, https://jeanpaulmartinon.net/wp-content/uploads/2018/07/Kagame-on-Time.pdf.

aiser, David. *How the Hippies Saved Physics: Science, Counterculture, and the Quantum Revival.* W. W. Norton & Company, 2012.

am, Chon-Fai, Cheng-Ning Zhang, and Da Hsuan Feng. “Chien-Shiung Wu's Trailblazing Experiments in Particle Physics.” *Physics Today* 77, no. 12 (December 1, 2024): 28–35, https://doi.org/10.1063/pt.oufp.zwkj.

earse, Stephen. “Childish Gambino: ‘This Is America.’ ” *Pitchfork,* https://pitchfork.com/reviews/tracks/childish-gambino-this-is-america/.

elley, Robin D. G. *Freedom Dreams: The Black Radical Imagination*. Beacon Press, 2022.

im, Bo-Young. *I'm Waiting for You: And Other Stories*. Translated by Sophie Bowman and Sung Ryu. Harper Voyager, 2021.

irshner, Robert P., Craig J. Hogan, and Nicholas B. Suntzeff. "Surveying Space-Time with Supernovae: Exploding Stars Seen Across Immense Distances Show That Cosmic Expansion May Be Accelerating." *Scientific American* 280, no. 1 (1999): 46, www.scientificamerican.com/article/surveying-space-time-with-supernova/.

ragh, Helge. *Higher Speculations: Grand Theories and Failed Revolutions in Physics and Cosmology*. Oxford University Press, 2015.

uwada, Brian Kamaoli. "We Live in the Future. Come Join Us." *KE KAUPU HEHI ALE* (blog), April 3, 2015, https://hehiale.com/2015/04/03/we-live-in-the-future-come-join-us/.

aymon, Kiese. *Long Division*. Scribner, 2021.

ear, Edward, and Vivien Noakes. *The Complete Nonsense and Other Verse*. Penguin, 2006.

ee, Stan, and Jack Kirby. *Amazing Fantasy. No. 15*. Marvel Comics, 1962.

iu, Cixin. *The Wandering Earth*. Tor, 2022.

ogsdon, John M. "John F. Kennedy and the 'Right Stuff.' " *Quest: The History of Spaceflight Quarterly,* 2013.

IacDougal, Douglas, Joseph Marcus, and Marcia Bartusiak. "Is It Time to Rename the Hubble Constant?" *Astronomy Magazine* (blog), December 3, 2024, www.astronomy.com/science/renaming-the-hubble-constant/.

Iaginsky, Jake, director. *Milford Graves Full Mantis*. Cinema Guild, 2018.

Iartin, Joseph D. *Solid State Insurrection: How the Science of Substance Made American Physics Matter*. University of Pittsburgh Press, 2018.

Iatthews, Airea D. *Simulacra*. Yale Series of Younger Poets, volume 111. Yale University Press, 2017.

Iaxwell, James Clerk. "A Dynamical Theory of the Electromagnetic Field." *Philosophical Transactions of the Royal Society of London* 155 (1865): 460.

Ibiti, John S. *African Religions & Philosophy*. Doubleday & Co., 1970.

IcKean, Benjamin Laing. *Disorienting Neoliberalism: Global Justice and the Outer Limit of Freedom*. Oxford University Press, 2020.

IcKittrick, Katherine. *Dear Science and Other Stories*. Duke University Press, 2021.

IcKittrick, Katherine, ed. *Sylvia Wynter: On Being Human as Praxis*. Duke University Press, 2015.

IcTier, Moiya. *The Milky Way: An Autobiography of Our Galaxy*. Grand Central, 2023.

Iedupe, Rodney Thebe, Brian Warner, Shamil Jeppie, Salikou Sanogo, Mohammed Maiga, Ahmed Maiga, et al. "The Timbuktu Astronomy Project: A Scientific Exploration of the Secrets of the Archives of Timbuktu." In *African Cultural Astronomy: Current Archaeoastronomy and Ethnoastronomy Research in Africa,* edited by Jarita C. Holbrook, Rodney Medupe, and Johnson O. Urama. Springer, 2008.

Ielville, Herman. *Moby-Dick: An Authoritative Text, Contexts, Criticism*. Edited by Hershel Parker. W. W. Norton & Company, 2018.

Iickens, Ronald E., ed. *Edward Bouchet: The First African-American Doctorate*. World Scientific, 2002.

Iickens, Ronald E. "The Life and Work of Elmer Samuel Imes." *Physics Today* 71, no. 10 (October 2018): 28–35.

Iickens, Ronald E. "Titus Pankey and the Supernova Ia Lightcurve." *History and Philosophy Physics: A Forum of the American Physical Society,* Fall 2024, https://higherlogicdownload.s3.amazonaws.com/APS/fc77d112-850f-4db6-997c-e434bd4670b5/UploadedImages/25017B_1_FHPP_Fall2024_FINAL.pdf.

Iiddleton, Listervelt. *On the Origins of Things: Poetry by Listervelt Middleton*. Independently published, 2022.

Iiles, Tiya. *All That She Carried: The Journey of Ashley's Sack, a Black Family Keepsake*. Random House, 2021.

________. *Night Flyer: Harriet Tubman and the Faith Dreams of a Free People*. Penguin Press, 2024.

iller, Matt W. *Tender the River: Poems*. Texas Review Press, 2021.

ilne, A. A. *When We Were Very Young*. Dutton, 1961.

intz, Sidney W., and Richard Price. *The Birth of African-American Culture: An Anthropological Perspective*. Beacon Press, 1992.

itchell, Koritha. "Identifying White Mediocrity and Know-Your-Place Aggression: A Form of Self-Care." *African American Review* 51, no. 4 (2018): 253–262.

itchell, Sean T. *Constellations of Inequality: Space, Race, and Utopia in Brazil*. University of Chicago Press, 2017.

itton, Jacqueline, and Simon Mitton. *Vera Rubin: A Life*. Harvard University Press, 2021.

ontgomery, Beronda L. *Lessons from Plants*. Harvard University Press, 2021.

oore, Donovan. *What Stars Are Made of: The Life of Cecilia Payne-Gaposchkin*. Harvard University Press, 2020.

oses, Robert P., and Charles E. Cobb Jr. *Radical Equations: Civil Rights from Mississippi to the Algebra Project*. Beacon Press, 2001.

ozi, and Ian Johnston. *The Mozi: A Complete Translation*. Translations from the Asian Classics. Columbia University Press, 2010.

uñoz, José Esteban. *Cruising Utopia: The Then and There of Queer Futurity*. New York University Press, 2019.

eedham, Joseph, and Wang Ling. *Science and Civilisation in China / by Joseph Needham, Vol. 4, Physics and Physical Technology; Part 1, Physics*. Cambridge University Press, 2004.

ewton, Isaac. *The Principia: Mathematical Principles of Natural Philosophy*. Translated by I. Bernhard Cohen and Anne Whitman. University of California Press, 1999.

jewale, Oluwole. "What Coltan Mining in the DRC Costs People and the Environment." *The Conversation,* May 29, 2022, http://theconversation.com/what-coltan-mining-in-the-drc-costs-people-and-the-environment-183159.

he On Being Project. "Remembering Nikki Giovanni—'We Go Forward with a Sanity and a Love.'" On Being, https://onbeing.org/programs/remembering-nikki-giovanni-we-go-forward-with-a-sanity-and-a-love/.

pata, Damian U. "Cultural Astronomy in the Lore and Literature of Africa." In *African Cultural Astronomy: Current Archaeoastronomy and Ethnoastronomy Research in Africa,* edited by Jarita C. Holbrook, Rodney Medupe, and Johnson O. Urama. Springer, 2008.

rosco, José-Antonio. *Star Trek's Philosophy of Peace and Justice: A Global, Anti-Racist Approach*. Bloomsbury, 2022.

rwell, George, and Erich Fromm. *1984*. Signet Classics, 2017.

verbye, Dennis. *Lonely Hearts of the Cosmos: The Scientific Quest for the Secret of the Universe*. HarperCollins, 1991.

aksi, Dániel. "The Concept of Boundary Conditions." *Polanyiana* 23, no. 1–2 (2014): 5–20.

eccei, R. D., and Helen R. Quinn. "Constraints Imposed by CP Conservation in the Presence of Pseudoparticles." *Physical Review D* 16, no. 6 (September 15, 1977): 1791–1797.

eebles, P.J.E. *Cosmology's Century: An Inside History of Our Modern Understanding of the Universe*. Princeton University Press, 2022.

opper, Karl R. *The Logic of Scientific Discovery*. Routledge, 2010.

oskett, James. *Horizons: The Global Origins of Modern Science*. HarperCollins Publishers, 2022.

oulin, Vivian, Tristan L. Smith, Tanvi Karwal, and Marc Kamionkowski. "Early Dark Energy Can Resolve the Hubble Tension." *Physical Review Letters* 122, no. 22 (June 4, 2019): 221301, https://doi.org/10.1103/PhysRevLett.122.221301.

rescod-Weinstein, Chanda. "Cosmic Acceleration as Quantum Gravity Phenomenology." PhD Thesis, University of Waterloo, 2010, http://hdl.handle.net/10012/5498.

________. “The Cosmos Is a Black Aesthetic.” *Differences* 35, no. 2 (September 1, 2024): 193–207.

________. *The Disordered Cosmos: A Journey into Dark Matter, Spacetime, and Dreams Deferred*. Bold Type Books, 2021.

rescod-Weinstein, Chanda, Sarah Tuttle, Lucian Walkowicz, and Brian Nord. “The James Webb Space Telescope Needs to Be Renamed.” *Scientific American*, May 1, 2021, www.scientificamerican.com/article/nasa-needs-to-rename-the-james-webb-space-telescope/.

)ueloz, Didier. “51 Pegasi b, and the Exoplanet Revolution.” Nobel Lecture presented Sunday, December 8, 2019, at the Aula Magna, Stockholm University, www.nobelprize.org/prizes/physics/2019/queloz/lecture/.

)uine, W. V. “The Scope and Language of Science.” *The British Journal for the Philosophy of Science* 8, no. 29 (May 1, 1957): 1–17.

apongan, Syaman (•). “The Eyes of the Sky.” Translated by Tim Smith. *The Willowherb Review*, 2022, www.thewillowherbreview.com/the-eyes-of-the-sky-syaman-rapongan-.

auch, Dominik, Johannes Handsteiner, Armin Hochrainer, Jason Gallicchio, Andrew S. Friedman, Calvin Leung, et al. “Cosmic Bell Test Using Random Measurement Settings from High-Redshift Quasars.” *Physical Review Letters* 121, no. 8 (August 20, 2018): 080403.

edhead, Michael. “A Philosopher Looks at Quantum Field Theory.” In *Philosophical Foundations of Quantum Field Theory,* edited by Harvey R. Brown and Rom Harré. Clarendon Press, 2001.

ich, Adrienne. *Collected Poems: 1950–2012*. W. W. Norton & Company, 2016.

iofrancos, Thea N. *Resource Radicals: From Petro-N ationalism to Post-Extractivism in Ecuador*. Radical Américas. Duke University Press, 2020.

ovelli, Carlo. “Notes for a Brief History of Quantum Gravity.” arXiv.org, June 16, 2000, https://arxiv.org/abs/gr-qc/0006061v3.

ubenstein, Mary-Jane. *Astrotopia: The Dangerous Religion of the Corporate Space Race*. University of Chicago Press, 2022.

ubin, Vera C., and W. Kent Ford Jr. “Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions.” *The Astrophysical Journal* 159 (February 1, 1970): 379.

utherford, Nathan, Chanda Prescod-Weinstein, and Anna Watts. “Probing Fermionic Asymmetric Dark Matter Cores Using Global Neutron Star Properties.” *Physical Review D* 111, no. 12 (June 23, 2025): 123034.

utherford, Nathan, Geert Raaijmakers, Chanda Prescod-Weinstein, and Anna Watts. “Constraining Bosonic Asymmetric Dark Matter with Neutron Star Mass-Radius Measurements.” *Physical Review D* 107, no. 10 (May 30, 2023): 103051.

agan, Carl. *The Cosmic Connection: An Extraterrestrial Perspective*. Anchor Press, 1973.

________. *Cosmos*. Random House, 1983.

aid, Wasim. *Witness to the Hellfire of Genocide: A Testimony from Gaza*. Translated by Muhammad Tutunji. 1804 Books, 2025.

chilling, Govert. *The Elephant in the Universe: Our Hundred-Year Search for Dark Matter*. Belknap Press, 2022.

coles, Sarah. “Behind the Scenes at a U.S. Factory Building New Nuclear Bombs.” *Scientific American,* December 1, 2023. https://www.scientificamerican.com/article/behind-the-scenes-at-a-u-s-factory-building-new-nuclear-bombs/.

ègla, Aimé Dafon. “The Cosmological Vision of the Yoruba-Idàácha of Benin Republic (West Africa): A Light on Yoruba History and Culture.” In *African Cultural Astronomy: Current Archaeoastronomy and Ethnoastronomy Research in Africa,* edited by Jarita C. Holbrook, Rodney Medupe, and Johnson O. Urama. Astrophysics and Space Science Proceedings. Springer, 2008.

hankar, Ramamurti. *Fundamentals of Physics II: Electromagnetism, Optics, and Quantum Mechanics.* Expanded edition. Open Yale Courses Series. Yale University Press, 2020.

harkey, Erin. "An Urban Farmer's Almanac." In *A Darker Wilderness: Black Nature Writing from Soil to Stars*, edited by Erin Sharkey. Milkweed Editions, 2023.

haw, A. R. *Trap History: Atlanta Culture and the Global Impact of Trap Music*. Bluefield Media, 2020.

hew, Ashley. *Against Technoableism: Rethinking Who Needs Improvement*. W. W. Norton & Company, 2023.

hotwell, Alexis. *Knowing Otherwise: Race, Gender, and Implicit Understanding*. Penn State University Press, 2015.

klar, Lawrence. *Space, Time, and Spacetime*. University of California Press, 1977.

mith, Tracy K. *Life on Mars: Poems*. Graywolf Press, 2011.

molin, Lee. *Three Roads to Quantum Gravity*. 2017 Edition. Basic Books, 2017.

obel, Dava. *The Glass Universe: How the Ladies of the Harvard Observatory Took the Measure of the Stars*. Penguin Publishing Group, 2016.

pinoza, Benedictus de. *Spinoza's Ethics and "De Intellectus Emendatione."* L. M. Dent & Sons, 1928.

ubramaniam, Banu. *Ghost Stories for Darwin: The Science of Variation and the Politics of Diversity.* University of Illinois Press, 2014.

uzuki, Koji. *Edge*. Translated by Camellia Nieh and Jonathan Lloyd-Davies. Kodansha, 2024.

weet, William. "France's Oppenheimer." *Physics Today* 78, no. 3 (March 1, 2025): 46–51.

amimi, Ahed. *"They Could Kill Me at Any Time": Life Under Israeli Occupation* (video), YouTube, 2022, www.youtube.com/watch?v=ZjKVpbXRvJo.

aylor, Paul C. *Black Is Beautiful: A Philosophy of Black Aesthetics*. Foundations of the Philosophy of Arts 6. Wiley Blackwell, 2016.

emple, Robert K. G. *The Genius of China: 3,000 Years of Science, Discovery, & Invention*. 1st U.S. Paperback Edition. Inner Traditions, 2007.

rethewey, Natasha. "On Abiding Metaphors and Finding a Calling." In *How We Do It: Black Writers on Craft, Practice, and Skill,* edited by Jericho Brown. Amistad, 2023.

———. "You Are Not Safe in Science; You Are Not Safe in History." *Southern Cultures* 26, no. 1 (Spring 2020), www.southerncultures.org/article/you-are-not-safe-in-science-you-are-not-safe-in-history-on-abiding-metaphors-and-finding-a-calling.

revithick, Joseph, and Tyler Rogoway. "If SpaceX's Secret Constellation Is What We Think It Is, It's Game Changing." TWZ, March 20, 2024, www.twz.com/space/if-spacexs-secret-constellation-is-what-we-think-it-is-its-game-changing.

enning, Thomas. "Time's Arrow: Albert Einstein's Letters to Michele Besso." Christies, November 14, 2017, www.christies.com/stories/einstein-letters-to-michele-besso-3ecca787d9be4463a8695269259d6c00.

Veinberg, Steven. *The First Three Minutes: A Modern View of the Origin of the Universe*. Updated Edition. Basic Books, 1993.

———. *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*. Wiley, 1976.

———. *The Quantum Theory of Fields, 1: Foundations*. Cambridge University Press, 2014.

Villiams, Saul, and Anisia Uzeyman, directors. *Neptune Frost*. Kino Lorber, 2021. 1 hr., 43 min, www.criterionchannel.com/videos/neptune-frost.

Vilson, Shawn. *Research Is Ceremony: Indigenous Research Methods*. Fernwood Publishing, 2008.

Voolf, Virginia. *A Room of One's Own*. Edited by Mark Hussey. Harcourt, 2005.

Vynter, Sylvia. "1492: A New World View." In *Race, Discourse, and the Origin of the Americas: A New World View,* edited by Vera Lawrence Hyatt, Rex Nettle-ford, and Smithsonian Institution. Smithsonian Institution Press, 1995.

affa AS. *Sage*. Meraj Publishing, 2025.
eager, Ashley Jean. *Bright Galaxies, Dark Matter, and Beyond: The Life of Astronomer Vera Rubin*. MIT Press, 2021.
u, Charles. *How to Live Safely in a Science Fictional Universe*. Vintage Contemporaries, 2011.

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