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Preface

"I do mathematics because once you prove a theorem, it stands. Forever."[1] The statement, simple and direct, was startling. I was a sophomore in college and had mentioned to an older friend, who for years had taught me vast areas of mathematics, that I was writing a paper on human motivation for a psychology course I was taking. His response was transformative. Until then, I hadn't thought about mathematics in terms even remotely similar. To me, math was a wondrous game of abstract precision played by a peculiar community who would delight at punch lines turning on square roots or dividing by zero. But with his remark, the cogs suddenly clicked. *Yes,* I thought. *That is the romance of mathematics.* Creativity constrained by logic and a set of axioms dictates how ideas can be manipulated and combined to reveal unshakable truths. Every right-angled triangle drawn from before Pythagoras and on to eternity satisfies the famous theorem that bears his name. There are no exceptions. Sure, you can change the assumptions and find yourself exploring new realms, such as triangles drawn on a curved surface like the skin of a basketball, which can upend Pythagoras's conclusion. But fix your assumptions, double-check your work, and your result is ready to be chiseled in stone. No climbing to the mountaintop, no wandering the desert, no triumphing over the underworld. You can sit comfortably at a desk and use paper, pencil, and a penetrating mind to create something timeless.

The perspective opened my world. I had never really asked myself *why* I was so deeply attracted to mathematics and physics. Solving problems, learning how the universe is put together—

that's what had always captivated me. I now became convinced that I was drawn to these disciplines because they hovered above the impermanent nature of the everyday. However overblown my youthful sensibilities rendered my commitment, I was suddenly sure I wanted to be part of a journey toward insights so fundamental that they would never change. Let governments rise and fall, let World Series be won and lost, let legends of film, television, and stage come and go. I wanted to spend my life catching a glimpse of something transcendent.

In the meantime, I still had that psychology paper to write. The assignment was to develop a theory of why we humans do what we do, but each time I started writing, the project seemed decidedly nebulous. If you clothed reasonable-sounding ideas in the right language it seemed that you could pretty much make it up as you went along. I mentioned this over dinner at my dorm and one of the resident advisors suggested I take a look at Oswald Spengler's *Decline of the West.* A German historian and philosopher, Spengler had an abiding interest in both mathematics and science, no doubt the very reason his book had been recommended.

The aspects responsible for the book's fame and scorn—predictions of political implosion, a veiled espousal of fascism—are deeply troubling and have since been used to support insidious ideologies, but I was too narrowly focused for any of this to register. Instead, I was intrigued by Spengler's vision of an all-encompassing set of principles that would reveal hidden patterns playing out across disparate cultures, on par with the patterns articulated by calculus and Euclidean geometry that had transformed understanding in physics and mathematics.[2] Spengler was talking my language. It was inspiring for a text on history to revere math and physics as a template for progress. But then came an observation that caught me thoroughly by surprise: "Man is the only being that knows death; all others become old, but with a consciousness wholly limited to the moment which must seem to them eternal," knowledge that instills the "essentially human fear in the presence of death." Spengler concluded that "every religion, every scientific investigation, every philosophy proceeds from it."[3]

I remember dwelling on the last line. Here was a perspective on human motivation that made sense to me. The enchantment of a mathematical proof might be that it stands forever. The appeal of a law of nature might be its timeless quality. But what drives us to seek the timeless, to search for qualities that may last forever? Perhaps it all comes from our singular awareness that we are anything but timeless, that our lives are anything but forever. Resonating with my newfound thinking on math, physics, and the allure of eternity, this felt on target. It was an approach to human motivation grounded in a plausible reaction to a pervasive recognition. It was an approach that didn't make it up on the fly.

As I continued to think about this conclusion, it seemed to promise something grander still. Science, as Spengler noted, is one response to the knowledge of our inescapable end. And so is religion. And so is philosophy. But, really, why stop there? According to Otto Rank, an early disciple of Freud who was fascinated by the human creative process, we surely shouldn't. The artist, in Rank's assessment, is someone whose "creative impulse . . . attempts to turn ephemeral life into personal immortality."[4] Jean-Paul Sartre went farther, noting that life itself is drained of meaning "when you have lost the illusion of being eternal."[5] The suggestion, then, threading its way through these and other thinkers who followed, is that much of human culture—from artistic exploration to scientific discovery—is driven by life reflecting on the finite nature of life.

Deep waters. Who knew that a preoccupation with all things mathematics and physics would tap into visions of a unified theory of human civilization driven by the rich duality of life and death?

Well, OK. I'll take a breath as I remind my long-ago sophomore self not to get too carried away. Nonetheless, the excitement I felt proved more than a passing wide-eyed intellectual wonderment. In the nearly four decades since, these themes, often simmering on a mental back burner, have stayed with me. While my day-to-day work has pursued unified theories and cosmic origins, in ruminating on the larger significance of scientific advances I have found myself returning repeatedly to questions of time and the limited allotment we are each given. Now, by training and temperament, I'm skeptical of one-size-fits-all explanations—physics is littered with unsuccessful unified theories of nature's forces—only more so if we venture into the complex realm of human behavior. Indeed, I have come to see my awareness of my own inevitable end as having considerable influence but not providing a blanket explanation for everything I do. It's an assessment, I imagine, that to varying degrees is common. Still, there is one domain in which mortality's tentacles are particularly evident.

Across cultures and through the ages, we have placed significant value on permanence. The ways we have done so are abundant: some seek absolute truth, others strive for enduring legacies, some build formidable monuments, others pursue immutable laws, and others still turn with fervor toward one or another version of the everlasting. Eternity, as these preoccupations demonstrate, has a powerful pull on the mind aware that its material duration is limited.

In our era, scientists equipped with the tools of experiment, observation, and mathematical analysis have blazed a new trail toward the future, one that for the first time has revealed prominent features of the eventual if still far-off landscape-to-be. Although obscured by mist here and fog there, the panorama is becoming sufficiently clear that we cogitating creatures can glean more fully than ever before how we fit into the grand expanse of time.

It is in this spirit, in the pages that follow, that we will walk the timeline of the universe, exploring the physical principles that yield orderly structures from stars and galaxies to life and consciousness, within a universe destined for decay. We will consider arguments establishing that much as human beings have limited life spans, so too do the very phenomena of life and mind in the universe. Indeed, at some point it is likely that organized matter of any kind will not be possible. We will examine how self-reflective beings contend with the tension entailed in these realizations. We emerge from laws that, as far as we can tell, are timeless, and yet we exist for the briefest moment of time. We are guided by laws that operate without concern for destination, and yet we constantly ask ourselves where we are headed. We are shaped by laws that seem not to require an underlying rationale, and yet we persistently seek meaning and purpose.

In short, we will survey the universe from the beginning of time to something akin to the end, and through the journey explore the breathtaking ways in which restless and inventive minds have illuminated and responded to the fundamental transience of everything.

We will be guided in the exploration by insights from a variety of scientific disciplines. Through analogies and metaphors, I explain all necessary ideas in nontechnical terms, presuming only the most modest background. For particularly challenging concepts, I provide brief summaries that allow you to move on without losing the trail. In the endnotes I explain finer points, spell out particular mathematical details, and provide references and suggestions for further reading.

Because the subject is vast and our pages limited, I have chosen to walk a tight path, pausing at various junctures I consider essential for recognizing our place within the larger cosmological story. It is a journey powered by science, given significance by humanity, and the source of a vigorous and enriching adventure.

UNTIL THE END OF TIME

1

THE LURE OF ETERNITY

Beginnings, Endings, and Beyond

In the fullness of time all that lives will die. For more than three billion years, as species simple and complex found their place in earth's hierarchy, the scythe of death has cast a persistent shadow over the flowering of life. Diversity spread as life crawled from the oceans, strode on land, and took flight in the skies. But wait long enough and the ledger of birth and death, with entries more numerous than stars in the galaxy, will balance with dispassionate precision. The unfolding of any given life is beyond prediction. The final fate of any given life is a foregone conclusion.

And yet this looming end, as inevitable as the setting sun, is something only we humans seem to notice. Long before our arrival, the thunderous clap of storm clouds, the raging might of volcanoes, the tremulous shudders of a quaking earth surely sent scurrying everything with the power to scurry. But such flights are an instinctual reaction to a present danger. Most life lives in the moment, with fear born of immediate perception. It is only you and I and the rest of our lot that can reflect on the distant past, imagine the future, and grasp the darkness that awaits.

It's terrifying. Not the kind of terror that makes us flinch or run for cover. Rather, it's a foreboding that quietly lives within us, one we learn to tamp down, to accept, to make light of. But underneath the obscuring layers is the ever-present, unsettling fact of what lies in store, knowledge that William James described as the "worm at the core of all our usual springs of delight."[1] To work and play, to yearn and strive, to long and love, all of it stitching us ever more tightly into the tapestry of the lives we share, and for it all then to be gone—well, to paraphrase Steven Wright, it's enough to scare you half to death. Twice.

Of course, most of us, in the service of sanity, don't fixate on the end. We go about the world focused on worldly concerns. We accept the inevitable and direct our energies to other things. Yet the recognition that our time is finite is always with us, helping to shape the choices we make, the challenges we accept, the paths we follow. As cultural anthropologist Ernest Becker maintained, we are under a constant existential tension, pulled toward the sky by a consciousness that can soar to the heights of Shakespeare, Beethoven, and Einstein but tethered to earth by a physical form that will decay to dust. "Man is literally split in two: he has an awareness of his own splendid uniqueness in that he sticks out of nature with a towering majesty, and yet he goes back into the ground a few feet in order blindly and dumbly to rot and disappear forever."[2] According to Becker, we are impelled by such awareness to deny death the capacity to erase us. Some soothe the existential yearning through commitment to family, a team, a movement, a religion, a nation—constructs that will outlast the individual's allotted time on earth. Others leave behind creative expressions, artifacts that extend the duration of their presence symbolically. "We fly to Beauty," said Emerson, "as an asylum from the terrors of finite nature."[3] Others still seek to vanquish death by winning or conquering, as if stature, power, and wealth command an immunity unavailable to the common mortal.

Across the millennia, one consequence has been a widespread fascination with all things, real or imagined, that touch on the timeless. From prophesies of an afterlife, to teachings of reincarnation, to entreaties of the windswept mandala, we have developed strategies to contend with knowledge of our impermanence and, often with hope, sometimes with resignation, to gesture toward eternity. What's new in our age is the remarkable power of science to tell a lucid story not only of the past, back to the big bang, but also of the future. Eternity itself may forever lie beyond the reach of our equations, but our analyses have already revealed that the universe we have come to know is transitory. From planets to stars, solar systems to galaxies, black holes to swirling nebulae, nothing is everlasting. Indeed, as far as we can tell, not only is each individual life finite, but so too is life itself. Planet earth, which Carl Sagan described as a “mote of dust suspended on a sunbeam,” is an evanescent bloom in an exquisite cosmos that will ultimately be barren. Motes of dust, nearby or distant, dance on sunbeams for merely a moment.

Still, here on earth we have punctuated our moment with astonishing feats of insight, creativity, and ingenuity as each generation has built on the achievements of those who have gone before, seeking clarity on how it all came to be, pursuing coherence in where it is all going, and longing for an answer to why it all matters.

Such is the story of this book.

Stories of Nearly Everything

We are a species that delights in story. We look out on reality, we grasp patterns, and we join them into narratives that can captivate, inform, startle, amuse, and thrill. The plural—narratives—is utterly essential. In the library of human reflection, there is no single, unified volume that conveys ultimate understanding. Instead, we have written many nested stories that probe different domains of human inquiry and experience: stories, that is, that parse the patterns of reality using different grammars and vocabularies. Protons, neutrons, electrons, and nature’s other particles are essential for telling the reductionist story, analyzing the stuff of reality, from planets to Picasso, in terms of their microphysical constituents. Metabolism, replication, mutation, and adaptation are essential for telling the story of life’s emergence and development, analyzing the biochemical workings of remarkable molecules and the cells they govern. Neurons, information, thought, and awareness are essential for the story of mind—and with that the narratives proliferate: myth to religion, literature to philosophy, art to music, telling of humankind’s struggle for survival, will to understand, urge for expression, and search for meaning.

These are all ongoing stories, developed by thinkers hailing from a great range of distinct disciplines. Understandably so. A saga that ranges from quarks to consciousness is a hefty chronicle. Still, the different stories are interlaced. *Don Quixote* speaks to humankind's yearning for the heroic, told through the fragile Alonso Quijano, a character created in the imagination of Miguel de Cervantes, a living, breathing, thinking, sensing, feeling collection of bone, tissue, and cells that, during his lifetime, supported organic processes of energy transformation and waste excretion, which themselves relied on atomic and molecular movements honed by billions of years of evolution on a planet forged from the detritus of supernova explosions scattered throughout a realm of space emerging from the big bang. Yet to read Don Quixote's travails is to gain an understanding of human nature that would remain opaque if embedded in a description of the movements of the knight-errant's molecules and atoms or conveyed through an elaboration of the neuronal processes crackling in Cervantes's mind while writing the novel. Connected though they surely are, different stories, told with different languages and focused on different levels of reality, provide vastly different insights.

Perhaps one day we will be able to transit seamlessly between these stories, connecting all products of the human mind, real and fictive, scientific and imaginative. Perhaps we will one day invoke a unified theory of particulate ingredients to explain the overwhelming vision of a Rodin and the myriad responses *The Burghers of Calais* elicits from those who experience it. Maybe we will fully grasp how the seemingly mundane, a glint of light reflecting from a spinning dinner plate, can churn through the powerful mind of a Richard Feynman and compel him to rewrite the fundamental laws of physics. More ambitious still, perhaps one day we will understand the workings of mind and matter so completely that all will be laid bare, from black holes to Beethoven, from quantum weirdness to Walt Whitman. But even without having anything remotely near that capacity, there is much to be gained by immersion in these stories—scientific, creative, imaginative—appreciating when and how they emerged from earlier ones playing out on the cosmic timeline and tracing the developments, both controversial and conclusive, that elevated each to their place of explanatory prominence.[4]

Clear across the collection of stories, we will find two forces sharing the role of leading character. In chapter 2 we will meet the first: *entropy.* Although familiar to many through its association with disorder and the often-quoted declaration that disorder is always on the rise, entropy has subtle qualities that allow physical systems to develop in a rich variety of ways, sometimes even appearing to swim against the entropic stream. We will see important examples of this in chapter 3, as particles in the aftermath of the big bang seemingly flout the drive to disorder as they evolve into organized structures like stars, galaxies, and planets—and ultimately, into configurations of matter that surge with the current of life. Asking how that current switched on takes us to the second of our pervasive influences: *evolution.*

Although it is the prime mover behind the gradual transformations experienced by living systems, evolution by natural selection kicks in well before the first forms of life start competing. In chapter 4, we will encounter molecules battling molecules, struggles for survival waged in an arena of inanimate matter. Round upon round of molecular Darwinism, as such chemical combat is called, is what likely produced a series of ever more robust configurations ultimately yielding the first molecular collections we would recognize as life. The details are the stuff of cutting-edge research, but with the last couple of decades of stupendous progress, the consensus is that we are heading down the right track. Indeed, it may be that the dual forces of entropy and evolution are well-matched partners in the trek toward the emergence of life. While that might sound like an odd coupling—entropy's public rap veers close to chaos, seemingly the antithesis of evolution or of life—recent mathematical analyses of entropy suggest that life, or at least lifelike qualities, might well be the *expected* product of a long-lived source of energy, like the sun, relentlessly raining down heat and light on molecular ingredients that are competing for the limited resources available on a planet like earth.

Tentative though some of these ideas currently are, what's certain is that a billion or so years after the earth formed it was teeming with life developing under evolutionary pressure, and so the next phase of developments is standard Darwinian fare. Chance events, like being hit by a cosmic ray or suffering a molecular mishap during the replication of DNA, result in random mutations, some with minimal impact on the organism's health or welfare but others making it more or less fit in the competition for survival. Those mutations that enhance fitness are more likely to be passed on to descendants because the very meaning of "more fit" is that the trait's carrier is more likely to survive to reproductive maturity and produce fit offspring. From generation to generation, qualities that enhanced fitness thus spread widely.

Billions of years later, as this long process continued to unfold, a particular suite of mutations provided some forms of life with an enhanced capacity for cognition. Some life not only became aware, but became aware of being aware. That is, some life acquired conscious self-awareness. Such self-reflective beings have naturally wondered what consciousness is and how it arose: How can a swirl of mindless matter think and feel? Various researchers, as we will discuss in chapter 5, anticipate a mechanistic explanation. They argue that we need to understand the brain—its components, its functions, its connections—with far greater fidelity than we now do, but once we have that knowledge, an explanation of consciousness will follow. Others anticipate that we are up against a far greater challenge, arguing that consciousness is the most difficult conundrum we have ever encountered, one that will require radically new perspectives regarding not just mind but also the very nature of reality.

Opinions converge when assessing the impact our cognitive sophistication has had on our behavioral repertoire. Across tens of thousands of generations during the Pleistocene, our forebears joined together in groups that subsisted through hunting and gathering. In time, an emerging mental dexterity provided them with refined capacities to plan and organize and communicate and teach and evaluate and judge and problem-solve. Leveraging these enhanced abilities of the individual, groups exerted increasingly influential communal forces. Which takes us to the next collection of explanatory episodes, those focused on developments that made us us. In chapter 6 we examine our acquisition of language and subsequent obsession with the telling of stories; chapter 7 probes a particular genre of stories, those that foreshadow and transition into religious traditions; and in chapter 8 we explore the longstanding and widespread pursuit of creative expression.

In seeking the origin of these developments, both common and sacred, researchers have invoked a wide range of explanations. For us, an essential guiding light will continue to be Darwinian evolution, applied now to human behavior. The brain, after all, is but another biological structure evolving via selection pressures, and it is the brain that informs what we do and how we respond. Over the past few decades, cognitive scientists and evolutionary psychologists have developed this perspective, establishing that much as our biology has been shaped by the forces of Darwinian selection, so too has our behavior. And thus in our trek across human culture we will often ask whether this or that behavior may have enhanced the prospects for survival and reproduction among those who long ago practiced it, promoting its wide propagation throughout generations of descendants. However, unlike the opposable thumb or upright gait—inherited physiological features tightly linked to specific adaptive behaviors—many of the brain's inherited characteristics mold predilections rather than definitive actions. We are influenced by these predispositions but human activity emerges from a comingling of behavioral tendencies with our complex, deliberative, self-reflective minds.

And so a second guiding light, distinct but no less important, will be trained on the inner life that comes hand in hand with our refined cognitive capacities. Following a trail marked by many thinkers, we will come to a revealing vista: with human cognition we surely harnessed a powerful force, one that in time elevated us to the dominant species worldwide. But the mental faculties that allow us to shape and mold and innovate are the very ones that dispel the myopia that would otherwise keep us narrowly focused on the present. The ability to manipulate the environment thoughtfully provides the capacity to shift our vantage point, to hover above the timeline and contemplate what was and imagine what will be. However much we'd prefer it otherwise, to achieve "I think, therefore I am" is to run headlong into the rejoinder "I am, therefore I will die."

Mildly put, the realization is disconcerting. Yet most of us can take it. And our survival as a species attests to our brethren having been able to take it too. But how do we do it?[5] According to one line of thought, we tell and retell stories in which our place in a vast universe migrates to center stage, and the possibility of our being permanently erased is challenged or is ignored—or, simply put, is just not in the cards. We craft works in painting, sculpture, movement, and music in which we wrest control of creation and invest ourselves with the power to triumph over all things finite. We envision heroes, from Hercules to Sir Gawain to Hermione, who stare down death with a steely resolve and demonstrate, albeit fancifully, that we can conquer. We develop science, providing insights into the workings of reality that we transform into powers earlier generations would have reserved for gods. In short, we can have our cognitive cake—the nimbleness of thought that, among much else, reveals our existential predicament—and enjoy eating it too. Through our creative capacities we have developed formidable defenses against what would otherwise have been debilitating disquiet.

All the same, because motives don't fossilize, tracing the inspiration for human behavior can be a knotty undertaking. Perhaps our creative forays, from the stags at Lascaux to the equations of general relativity, emerge from the brain's naturally selected but overly active ability to detect and coherently organize patterns. Perhaps these and related pursuits are exquisite but adaptively superfluous by-products of a sufficiently large brain released from full-time focus on securing shelter and sustenance. As we will discuss, theories abound but unassailable conclusions are elusive. What lies beyond question is that we imagine and we create and we experience works, from the Pyramids to the Ninth Symphony to quantum mechanics, that are monuments to human ingenuity whose durability, if not whose content, point toward permanence.

And with that, having considered cosmic origins, explored the formation of atoms, stars, and planets, and swept across the emergence of life, consciousness, and culture, we will cast our sights toward the very realm that for millennia, literally and symbolically, has both stimulated and quelled our cosmic anxiety. We will look, that is, from here to eternity.

Information, Consciousness, and Eternity

Eternity will be a long time coming. A lot will happen along the way. Breathless futurists and Hollywood sci-fi spectaculars envision what life and civilization will be like over spans that while significant by human standards pale in comparison to cosmic timescales. It is an entertaining pastime to extrapolate from a short stretch of exponential technological innovation to future developments, but such predictions are likely to differ profoundly from how things will actually unfold. And that's over relatively familiar durations of decades, centuries, and millennia. Over cosmic timescales, predicting these sorts of details is a fool's errand. Thankfully, for most of what we will explore here, we will find ourselves on more solid ground. My intent is for us to paint the future of the universe with rich colors but only with the broadest of strokes. And with that level of detail, we can portray the possibilities with a reasonable degree of confidence.

An essential recognition is that there is little emotional equanimity to be gained from leaving a trace on a future bereft of anyone there to notice. The future we tend to envision, even if only implicitly, is one that's populated by the kinds of things we care about. Evolution will surely drive life and mind to take on a wealth of forms supported by a range of platforms—biological, computational, hybrid, and who knows what else. But regardless of the unpredictable details of physical composition or environmental backdrop, most of us imagine that in the vastly distant future, life of some stripe, and intelligent life more particularly, will exist and it will think.

And this raises a question that will ride along with us throughout the journey: Can conscious thought persist indefinitely? Or might the thinking mind, like the Tasmanian tiger or the ivory-billed woodpecker, be something sublime that rises up for a period but then goes extinct? I'm not focused on any individual consciousness, so the question has nothing to do with wished-for technologies—cryogenic, digital, whatever—capable of preserving a given mind. Instead, I am asking whether the phenomenon of thought, supported by a human brain or an intelligent computer or entangled particles floating in the void or any other physical process that proves relevant, can persist arbitrarily far into the future.

Why wouldn't it? Well, think about the human incarnation of thought. It arose in conjunction with a fortuitous set of environmental conditions explaining why, for example, our thinking takes place here and not on Mercury or on Halley's comet. We think here because the conditions here are hospitable to life and thought, which is why deleterious changes to earth's climate are so distressing. What's not at all obvious is that there is a cosmic version of such consequential but parochial concerns. By thinking of thought as a physical process (an assumption we will examine), it is not surprising that thought can take place only when certain stringent environmental conditions are met, whether on earth in the here and now or somewhere else in the there and then. And so as we consider the broad-brush evolution of the universe, we will determine whether the evolving environmental conditions across space and time can support intelligent life indefinitely.

The assessment will be guided by insights from research in particle physics, astrophysics, and cosmology that allow us to predict how the universe will unfold over epochs that dwarf the timeline back to the bang. There are significant uncertainties, of course, and like most scientists I live for the possibility that nature will slap down our hubris and reveal surprises we can't yet fathom. But focusing on what we've measured, on what we've observed, and on what we've calculated, what we'll find, as laid out in chapters 9 and 10, is not heartening. Planets and stars and solar systems and galaxies and even black holes are transitory. The end of each is driven by its own distinctive combination of physical processes, spanning quantum mechanics through general relativity, ultimately yielding a mist of particles drifting through a cold and quiet cosmos.

How will conscious thought fare in a universe experiencing such transformation? The language for asking and answering this question is provided once again by entropy. And by following the entropic trail we will encounter the all-too-real possibility that the very act of thinking, undertaken by any entity of any kind anywhere, may be thwarted by an unavoidable buildup of environmental waste: in the distant future, anything that thinks may burn up in the heat generated by its own thoughts. Thought itself may become physically impossible.

While the case against endless thought will be based on a conservative set of assumptions, we will also consider alternatives, possible futures more conducive to life and thinking. But the most straightforward reading suggests that life, and intelligent life in particular, is ephemeral. The interval on the cosmic timeline in which conditions allow for the existence of self-reflective beings may well be extremely narrow. Take a cursory glance at the whole shebang, and you might miss life entirely. Nabokov's description of a human life as a "brief crack of light between two eternities of darkness"[6] may apply to the phenomenon of life itself.

We mourn our transience and take comfort in a symbolic transcendence, the legacy of having participated in the journey at all. You and I won't be here, but others will, and what you and I do, what you and I create, what you and I leave behind contributes to what will be and how future life will live. But in a universe that will ultimately be devoid of life and consciousness, even a symbolic legacy—a whisper intended for our distant descendants—will disappear into the void.

Where, then, does that leave us?

Reflections on the Future

We tend to absorb findings about the universe intellectually. We learn some new fact about time or unified theories or black holes. It momentarily tickles the mind, and if sufficiently impressive, it sticks. The abstract nature of science often leads us to dwell on its content cognitively, and only then, and then only rarely, does that understanding have a chance of touching us viscerally. But on the occasions when science does conjure both reason and emotion, the result can be powerful.

Case in point: Some years ago when I began to think about scientific predictions regarding the far future of the universe, my experience was mostly cerebral. I absorbed relevant material as a fascinating but abstract collection of insights entailed by the mathematics of nature's laws. Still, I found that if I pressed myself to *really* imagine all life, all thought, all struggle, and all accomplishment being a fleeting aberration on an otherwise lifeless cosmic timeline, I absorbed it differently. I could sense it. I could feel it. And I don't mind sharing that the first few times I went there, the journey was dark. Through decades of study and scientific research, I've often had moments of elation and wonder, but never previously had results in mathematics and physics overwhelmed me with a hollow dread.

Over time, my emotional engagement with these ideas has refined. Now, more often than not, contemplating the far future leaves me with a feeling of calm and connection, as if my own identity hardly matters because it has been subsumed by what I can only describe as a feeling of gratitude for the gift of experience. Since, more than likely, you don't know me personally, let me put this in context. I'm open-minded with a sensibility that demands rigor. I come from a world in which you make your case with equations and replicable data, a world in which validity is determined by unambiguous calculations that yield predictions matching experiments digit by digit, sometimes as far as a dozen places beyond the decimal point. So the first time I had one of these moments of calm connection—I happened to be at a Starbucks in New York City—I was deeply suspicious. Perhaps my Earl Grey was tainted with some bad soy milk. Or perhaps I was losing my mind.

On reflection, neither was the case. We are the product of a long lineage that has soothed its existential discomfort by envisioning that we leave a mark. And the more lasting the mark, the more indelible its imprint, the more a life seems to be a life that mattered. In the words of philosopher Robert Nozick—but they could just as easily have come from George Bailey—"Death wipes you out . . . To be wiped out completely, traces and all, goes a long way toward destroying the meaning of one's life."[7] Especially for those, like me, without a traditional religious orientation, an emphasis on not being "wiped out," a relentless focus on endurance, can pervade everything. My upbringing, my education, my career, my experiences have all been informed by it. During every stage, I've gone forward with an eye trained on the long view, on seeking to accomplish something that would last. There is no mystery why my professional preoccupation has been dominated by mathematical analyses of space, time, and nature's laws; it is hard to imagine another discipline that more readily keeps one's day-to-day thoughts focused on questions that transcend the moment. But scientific discovery itself casts this perspective in a different light. Life and thought likely populate a minute oasis on the cosmic timeline. Though governed by elegant mathematical laws that allow for all manner of wondrous physical processes, the universe will play host to life and mind only temporarily. If you take that in fully, envisioning a future bereft of stars and planets and things that think, your regard for our era can appreciate toward reverence.

And *that* is the feeling I had experienced at Starbucks. The calm and connection marked a shift from grasping for a receding future to the feeling of inhabiting a breathtaking if transient present. It was a shift, for me, compelled by a cosmological counterpart to the guidance offered through the ages by poets and philosophers, writers and artists, spiritual sages and mindfulness teachers, among countless others who tell us the simple but surprisingly subtle truth that life is in the here and now. It's a mind-set that is hard to maintain but one that has infused the thinking of many. We see it in Emily Dickinson's "Forever—is composed of Nows"[8] and Thoreau's "eternity in each moment."[9] It is a perspective, I've found, that becomes all the more palpable when we immerse ourselves in the full expanse of time—beginning to end—a cosmological backdrop that provides unmatched clarity on how singular and fleeting the here and now actually is.

The purpose of this book is to provide that clarity. We will journey across time, from our most refined understanding of the beginning to the closest science can take us to the very end. We will explore how life and mind emerge from the initial chaos, and we will dwell on what a collection of curious, passionate, anxious, self-reflective, inventive, and skeptical minds do, especially when they notice their own mortality. We will examine the rise of religion, the urge for creative expression, the ascent of science, the quest for truth, and the longing for the timeless. The deep-seated affinity for something permanent, for what Franz Kafka identified as our need for "something indestructible,"[10] will then propel our continued march toward the distant future, allowing us to assess the prospects for everything we hold dear, everything constituting reality as we know it, from planets and stars, galaxies and black holes, to life and mind.

Across it all, the human spirit of discovery will shine through. We are ambitious explorers seeking to grasp a vast reality. Centuries of effort have illuminated dark terrains of matter, mind, and the cosmos. During millennia to come, the spheres of illumination will grow larger and brighter. The journey so far has already made evident that reality is governed by mathematical laws that are indifferent to codes of conduct, standards of beauty, needs for companionship, longings for understanding, and quests for purpose. Yet, through language and story, art and myth, religion and science, we have harnessed our small part of the dispassionate, relentless, mechanical unfolding of the cosmos to give voice to our pervasive need for coherence and value and meaning. It is an exquisite but temporary contribution. As our trek across time will make clear, life is likely transient, and all understanding that arose with its emergence will almost certainly dissolve with its conclusion. Nothing is permanent. Nothing is absolute. And so, in the search for value and purpose, the only insights of relevance, the only answers of significance, are those of our own making. In the end, during our brief moment in the sun, we are tasked with the noble charge of finding our own meaning.

Let us embark.

2

THE LANGUAGE OF TIME

Past, Future, and Change

On the evening of January 28, 1948, nestled between a performance of the Schubert Quartet in A minor and a presentation of English folk songs, BBC Radio broadcast a debate between one of the most potent intellectual forces of the twentieth century, Bertrand Russell, and Jesuit priest Frederick Copleston.[1] The topic? The existence of God. Russell, whose innovative writings in philosophy and humanitarian principles would earn him the 1950 Nobel Prize in Literature, and whose iconoclastic political and social views would earn him a pink slip from both Cambridge University and the City College of New York, provided numerous arguments for questioning, if not rejecting, the existence of a creator.

One line of thought that informed Russell's position is relevant to our exploration here. "So far as scientific evidence goes," Russell noted, "the universe has crawled by slow stages to a somewhat pitiful result on this earth and is going to crawl by still more pitiful stages to a condition of universal death." With such a bleak outlook, Russell concluded, "if this is to be taken as evidence of purpose, I can only say that the purpose is one that does not appeal to me. I see no reason, therefore, to believe in any sort of God."[2] The theological thread will be stitched into later chapters. Here, I want to focus on Russell's reference to scientific evidence for a "universal death." It comes from a nineteenth-century discovery with roots as humble as its conclusions are profound.

By the mid-1800s, the Industrial Revolution was in full swing and across a landscape of mills and factories the steam engine had become the workhorse driving production. Nevertheless, even with the critical leap from manual to mechanical labor, the efficiency of the steam engine—the useful work performed compared to the quantity of fuel consumed—was meager. Roughly 95 percent of the heat generated by burning wood or coal was lost to the environment as waste. This inspired a handful of scientists to think deeply about the physical principles governing steam engines, seeking ways to burn less and get more. Over the course of many decades their research gradually led to an iconic result that has become justly famous: *the second law of thermodynamics.*

In (highly) colloquial terms, the law declares that the production of waste is unavoidable. And what makes the second law vitally important is that while steam engines were the catalyst, the law is universally applicable. The second law describes a fundamental characteristic inherent in all matter and energy, regardless of structure or form, whether animate or inanimate. The law reveals (loosely, again) that everything in the universe has an overwhelming tendency to run down, to degrade, to wither.

Stated in these everyday terms you can see where Russell was coming from. The future seemingly holds a continued deterioration, a relentless conversion of productive energy into useless heat, a steady draining, so to speak, of the batteries powering reality. But a more precise understanding of the science reveals that this summary of where reality is headed obscures a rich and nuanced progression, one that has been under way since the big bang and will carry onward to the far future. It is a progression that helps explain our place in the cosmic timeline, clarifies how beauty and order can be produced against a backdrop of degradation and decay, and also offers potential ways, exotic though they may be, to sidestep the bleak end Russell envisioned. As it is this very science, involving concepts such as entropy, information, and energy, that will guide much of our journey, it is worth our while to spend a little time understanding it more fully.

Steam Engines

Far be it from me to suggest that the meaning of life will be found lurking in the sweaty depths of a clamorous steam engine. But understanding the steam engine's capacity to absorb heat from burning fuel and use it to drive recurrent motion in a locomotive's wheels or a coal mine's pump proves indispensable to grasping how energy—of any sort and in any context—evolves over time. And the way energy evolves has a deep impact on the future of matter, mind, and all structure in the universe. So let's descend from the lofty realms of life and death and purpose and meaning to the incessant chugging and clanking of an eighteenth-century steam engine.

The scientific basis of the steam engine is simple but ingenious: Water vapor—steam—expands when heated and so pushes outward. A steam engine harnesses this action by heating a canister filled with steam that is capped by a snuggly fitting piston free to slide up and down along the canister's inner surface. As the heated steam expands, it pushes forcefully against the piston, and that outward thrust can drive a wheel to turn, or a mill to grind, or a loom to weave. Then, having expended energy through this outward exertion, the steam cools and the piston slides back to its initial position, where it stands ready to be pushed when the steam is heated again—a cycle that will repeat so long as there is burning fuel to heat the steam anew.[3]

While history records the steam engine's central role in the Industrial Revolution, the questions it raised for fundamental science were just as significant. Can we understand the steam engine with mathematical precision? Is there a limit to how efficient its conversion of heat into useful activity can be? Are there aspects of the steam engine's basic processes that are independent of the details of mechanical design or materials used and thus speak to universal physical principles?

In puzzling over these issues, the French physicist and military engineer Sadi Carnot launched the field of thermodynamics—the science of heat, energy, and work. You wouldn't have known it from sales of his 1824 treatise, *Reflections on the Motive Power of*

Fire.[4] But while slow to catch on, his ideas would inspire scientists over the course of the following century to develop a radically new perspective on physics.

A Statistical Perspective

The traditional scientific perspective, handed down in mathematical form by Isaac Newton, is that physical laws provide ironclad predictions for how things move. Tell me the location and velocity of an object at a particular moment, tell me the forces that are acting upon it, and Newton's equations do the rest, predicting the object's subsequent trajectory. Be it the moon pulled by earth's gravity or a baseball you just whacked toward center field, observations have confirmed that these predictions are spot-on accurate.

But here's the thing. If you took high school physics, perhaps you will recall that when we analyze the trajectories of macroscopic objects we generally, if quietly, invoke a great many simplifications. For the moon and the baseball we ignore their internal structure and imagine that each is just a single massive particle. It's a coarse approximation. Even a grain of salt contains about a billion billion molecules, and that's, well, a grain of salt. Yet as the moon orbits we generally don't care about the jostling motion of one or another molecule inhabiting the dusty Sea of Tranquility. As the baseball soars, we don't care about the vibration of one or another molecule residing in its cork core. The overall movement of the moon or the baseball as a whole is all we're after. And for that, applying Newton's laws to these simplified models does the trick.[5]

These successes highlight the challenge faced by nineteenth-century physicists concerned with steam engines. The hot steam pushing against the engine's piston comprises an enormous number of water molecules, perhaps a trillion trillion particles. We can't ignore this internal structure as we do in our analysis of the moon or the baseball. It is the motion of these very particles—slamming into the piston, bouncing off its surface, hitting the walls of the container, streaming back toward the piston again—that lies at the heart of the engine's workings. The problem is that there is no way that anyone, anywhere, however smart they may be and however formidable the computers they may use, can calculate all of the individual trajectories followed by such an enormous collection of water molecules.

Are we stuck?

You might think so. But as it turns out, we are saved by a change in perspective. Large collections can sometimes yield their own powerful simplifications. It is surely difficult, impossible really, to predict exactly when you will next sneeze. However, if we broaden our view to the larger collection of all humans on earth, we *can* predict that in the next second there'll be roughly eighty thousand sneezes worldwide.[6] The point is that by shifting to a statistical perspective, earth's large population becomes the key—not the obstacle—to predictive power. Large groups often display statistical regularities absent at the level of the individual.

An analogous approach for large groups of atoms and molecules was pioneered by James Clerk Maxwell, Rudolf Clausius, Ludwig Boltzmann, and many of their colleagues. They advocated jettisoning detailed consideration of individual trajectories in favor of statistical statements describing the average behavior of large collections of particles. They showed that this approach not only makes calculations mathematically tractable, but the physical properties it can quantify are the very ones that matter most. The pressure pushing on a steam engine's piston, for instance, is hardly affected by the precise path followed by this or that individual water molecule. Instead, the pressure arises from the average motion of the trillions upon trillions of molecules that slam into its surface each second. *That's* what matters. And *that's* what the statistical approach allowed the scientists to calculate.

In our current era of political polls, population genetics, and big data more generally, the shift to a statistical framework might not sound radical. We've grown accustomed to the power of statistical insights extracted from studying large groups. But in the nineteenth and early twentieth centuries, statistical reasoning was a departure from the rigid precision that had come to define physics. Bear in mind, too, that up through the early years of the twentieth century there were still well-respected scientists who challenged the existence of atoms and molecules—the very basis of a statistical approach.

Notwithstanding the naysayers, it didn't take long for statistical reasoning to prove its worth. In 1905, Einstein himself quantitatively explained the jittery motion of pollen grains suspended in a glass of water by invoking the continual bombardment by H_2O molecules. With that success, you had to be one heck of a contrarian to doubt the existence of molecules. What's more, a growing archive of theoretical and experimental papers revealed that conclusions based on statistical analyses of large collections of particles—describing how they bounce around containers and thereby exert pressure on this surface, or acquire that density, or relax to that temperature—matched data so exquisitely that there was simply no room to question the explanatory power of the approach. The statistical basis for thermal processes was thus born.

This was all a great triumph and has allowed physicists to understand not only steam engines but also a broad range of thermal systems—from earth's atmosphere, to the solar corona, to the vast collection of particles swarming within a neutron star. But how does this relate to Russell's vision of the future, his prognostication of a universe crawling toward death? Good question. Hang tight. We're getting there. But we still have a couple of steps to go. The next is to use these advances to shed light on the quintessential quality of the future: it differs profoundly from the past.

From This to That

The distinction between past and future is at once basic and pivotal to human experience. We were born in the past. We will die in the future. In between, we witness innumerable happenings that unfold through a sequence of events that, if considered in reverse order, would appear absurd. Van Gogh painted *Starry Night* but could not then lift the swirling colors through reverse brushstrokes, restoring a blank canvas. The *Titanic* scraped along an iceberg and ripped open its hull but could not then reverse engines, retrace its path, and undo the damage. Each one of us grows and ages but we cannot then turn back the hands of our internal clocks and reclaim our youth.

With irreversibility being so central to how things evolve, you would think we could easily identify its mathematical origin within the laws of physics. Surely, we should be able to point to something specific in the equations that ensures that although things can transform from *this* to *that,* the math forbids them from transforming from *that* to *this.* But for hundreds of years the equations we've developed have failed to offer us anything of the sort. Instead, as the laws of physics have been continually refined, passing through the hands of Newton (classical mechanics), Maxwell (electromagnetism), Einstein (relativistic physics), and the dozens of scientists responsible for quantum physics, one feature has remained stable: the laws have steadfastly adhered to a complete insensitivity to what we humans call future and what we call past. Given the state of the world right now, the mathematical equations treat unfolding toward the future or the past in exactly the same way. While that distinction matters to us, profoundly so, the laws shrug at the difference, assessing it as of no greater consequence than a stadium's game clock ticking off time elapsed or time remaining. Which means that if the laws allow for a particular sequence of events to occur, then the laws necessarily permit the reverse sequence too.[7]

As a student, when I first learned about this, it struck me as just shy of ludicrous. In the real world we don't see Olympic divers popping out of pools feetfirst and landing calmly on springboards. We don't see shards of stained glass jumping up from the floor and reassembling into a Tiffany lamp. Clips from films run in reverse are amusing for the very reason that what we see projected differs so thoroughly from anything we experience. And yet, according to the math, the events depicted in reverse-run clips are fully in keeping with the laws of physics.

Why then is our experience so lopsided? Why do we only ever see events unfold in one temporal orientation and never the reverse? A key part of the answer is revealed by the notion of *entropy,* a concept that will be essential to our understanding of the cosmic unfolding.

Entropy: A First Pass

Entropy is among the more confusing concepts in fundamental physics, a fact that has not diminished the cultural appetite for freely invoking it to describe everyday situations that have evolved from order to chaos or, more simply, from good to bad. As colloquial usage goes, this is fine; at times, I've invoked entropy that way too. But as the scientific conception of entropy will guide our journey—and also lies at the heart of Russell's dark vision of the future—let's tease out its more precise meaning.

Start with an analogy. Imagine you vigorously shake a bag containing a hundred pennies and then dump them out on your dining room table. If you found that all hundred pennies were heads, you'd surely be surprised. But why? Seems obvious, but it's worth thinking through. The absence of even a single tail means each of the hundred coins, randomly flipping, bumping, and jostling, must hit the table and land heads up. All of them. That's tough. Getting that unique outcome is a tall order. By comparison, if we consider even a slightly different outcome, say in which we have a single tail (and the other 99 pennies are still all heads), there are a hundred different ways this can happen: the lone tail could be the first coin, or it could be the second coin, or the third, and so on up to the hundredth coin. Getting 99 heads is thus a hundred times easier—a hundred times more likely—than getting all heads.

Let's keep going. A little figuring reveals that there are 4,950 different ways we can get two tails (first and second coins tails; first and third tails; second and third tails; first and fourth tails; and so forth). A little more figuring and we find that there are 161,700 different ways to have three of the coins come up tails, almost 4 million ways to have four tails; and about 75 million ways to have five tails. The details of the numbers hardly matter; it's the overall trend I'm driving at. Each additional tail allows for a far larger collection of outcomes that fit the bill. Phenomenally larger. The numbers peak at 50 tails (and 50 heads), for which there are about a hundred billion billion billion possible combinations (well, 100,891,344,545,564,193,334,812,497,256 combinations).[8] Getting

50 heads and 50 tails is therefore about a hundred billion billion billion times more likely than getting all heads.

That's why getting all heads would be shocking.

My explanation relies on the fact that most of us intuitively analyze the collection of pennies much as Maxwell and Boltzmann advocated analyzing a container of steam. Just as the scientists turned a cold shoulder to analyzing the steam molecule by molecule, we typically don't evaluate a random collection of pennies coin by coin. We hardly care or notice if the 29th penny is heads or the 71st is tails. Instead, we look at the collection as a whole. And the feature that catches our attention is the number of heads compared to the number of tails: Are there more heads than tails or more tails than heads? Twice as many? Three times as many? Roughly equal amounts? We can detect significant changes in the ratio of heads to tails, but random rearrangements that preserve the ratio—like flipping the 23rd, 46th, and 92nd coins from tails to heads while also flipping the 17th, 52nd, and 81st coins from heads to tails—are virtually indistinguishable. Consequently, I divvied up the possible outcomes into groups, each containing those configurations of coins that pretty much look the same, and I enumerated the membership of each group: I counted the number of outcomes with no tails, the number of outcomes with 1 tail, the number of outcomes with 2 tails, and so on, up to the number of outcomes with 50 tails.

The key realization is that these groups do not have equal membership. Not even close. That made it obvious why you'd be shocked for a random shake of the pennies to yield no tails (a group with precisely 1 member), slightly less shocked for a random shake to yield one tail (a group with 100 members), a touch less shocked still to find two tails (a group with 4,950 members), but you'd yawn if the shake yields a configuration that's half heads and half tails (a group with roughly one hundred billion billion billion members). The greater the membership in a given group, the more likely it is that a random outcome will belong to that group. Group size matters.

If this material is new to you, you may not realize that we have now illustrated the essential concept of entropy. The entropy of a given configuration of the pennies is the size of its group—the number of fellow configurations that pretty much look like the given configuration.[9] If there are many such look-alikes, the given configuration has high entropy. If there are few such look-alikes, the given configuration has low entropy. All else being equal, a random shake is more likely to belong to a group with higher entropy since such groups have more members.

This formulation also connects with the colloquial uses of entropy I referenced at the outset of this section. Intuitively, messy configurations (think of a chaotic desktop piled high with scattered documents, pens, and paper clips) have high entropy because a great many rearrangements of the constituents all pretty much look the same; randomly rearrange a messy configuration and it still looks messy. Orderly configurations (think of a pristine desktop with all documents, pens, and paper clips neatly placed in their designated positions) have low entropy because very few rearrangements of the constituents look the same. As with the pennies, high entropy beckons because messy arrangements far outnumber orderly ones.

Entropy: The Real Deal

The pennies are particularly useful because they illustrate the approach scientists developed for dealing with the voluminous collection of particles constituting physical systems, whether water molecules flitting to and fro in a hot steam engine or air molecules drifting across the room in which you are now breathing. As with the pennies, we ignore the details of individual particles—whether any one particular molecule of water or air happens to be here or there is of little consequence—and instead group together those configurations of the particles that pretty much look the same. For the pennies, the criterion for look-alikes invoked the ratio of heads to tails because typically we are indifferent to the disposition of any particular coin, and generally take note only of the configuration's overall appearance. But what does "pretty much look the same" mean for a large collection of gas molecules?

Think about the air now filling your room. If you're like me and the rest of us, you couldn't care less whether this molecule of oxygen is flitting by the window or that molecule of nitrogen is bouncing off the floor. You care only that each time you inhale there is an adequate volume of air to meet your needs. Well, there are a couple of other features you likely care about too. If the air's temperature was so hot that you scorched your lungs, you'd be unhappy. Or if the air's pressure was so high (and you hadn't equalized it with the air already in your eustachian tubes) that you burst your eardrums, you'd be unhappy too. Your concern, then, is with the air's volume, the air's temperature, and the air's pressure. Indeed, these are the very macroscopic qualities that physicists from Maxwell and Boltzmann on through today care about too.

Accordingly, for a large collection of molecules in a container, we say that different configurations "pretty much look the same" if they fill out the same volume, have the same temperature, and exert the same pressure. Much as with the pennies, we group together all look-alike configurations of the molecules and say that each member of the group gives rise to the same *macrostate*. The entropy of the macrostate is the number of such look-alikes. Assuming you are not just now turning on a space heater (affecting temperature) or putting up an impermeable room divider (affecting volume), or pumping in additional oxygen (affecting pressure), the ever-evolving configuration of air molecules flitting to and fro in the room you are now inhabiting all belong to the same group—they all pretty much look the same—as they all yield the very same macroscopic features you are currently experiencing.

The organization of particles into groups of look-alikes provides an extraordinarily powerful schema. Just as randomly tossed pennies are more likely to belong to a group with greater membership (with higher entropy), so too for randomly bouncing particles. The realization is as straightforward as its implications are far-reaching: Whether the bouncing particles are in a steam engine, in your room, or anywhere else, by understanding the typical features of the most commonplace configurations (those that belong to the groupings with the greatest membership), we can make predictions about the system's macroscopic qualities—the very qualities we care about. These are statistical predictions, to be sure, but ones with a fantastically high probability of being accurate. And the kicker is that we achieve all this while avoiding the insurmountable complexity of analyzing the trajectories of an absurdly large number of particles.

To carry out the program we therefore need to sharpen our ability to identify commonplace (high entropy) versus rare (low entropy) particle configurations. That is, given the state of a physical system, we need to determine whether there are many or few rearrangements of the constituents that would leave the system looking pretty much the same. As a case study, let's visit your steam-filled bathroom just after you've taken a long hot shower. To determine the steam's entropy, we need to count the number of configurations of the molecules—their possible positions and their possible speeds—that all have the same macroscopic properties, i.e., have the same volume, same temperature, and same pressure.[10] Carrying out the count mathematically for a collection of H_2O molecules is more challenging than the analogous count for a collection of pennies, but is something most physics majors learn to do by their sophomore year. More straightforward, and more enlightening too, is working out how volume, temperature, and pressure qualitatively affect entropy.

Volume first. Imagine that the flitting H_2O molecules are tightly clustered in one tiny corner of your bathroom, creating a dense knot of steam. In this configuration, the possible rearrangements of the positions of the molecules will be sharply curtailed; as you move the H_2O molecules around, you have to keep them within that knot or else the modified configuration *will* look different. By comparison, when the steam is evenly spread throughout your bathroom, the game of molecular musical chairs is far less constrained. You can exchange the positions of molecules near the vanity with those floating by the light fixture, those near the shower curtain with those hovering by the window, and yet, overall, the steam will look the same. Note too that the bigger your bathroom, the greater the number of locations you have for sprinkling around the molecules, which also increases the number of rearrangements available. The conclusion, then, is that smaller and tightly clustered configurations of molecules have lower entropy, while larger and evenly spread configurations have higher entropy.

Temperature next. At the level of molecules, what do we mean by temperature? The answer is well-known. Temperature is the average speed of a collection of molecules.[11] Something is cold when the average speed of its molecules is low and it is hot when the average speed is high. So determining how temperature affects entropy is tantamount to determining how the average molecular speed affects entropy. And much as we found with molecular positions, a qualitative assessment is close at hand. If the temperature of the steam is low, the allowed rearrangements of the molecular speeds will be comparatively few in number: to keep the temperature fixed—and thus ensure that the configurations all pretty much look the same—you have to offset any increase in the speeds of some molecules by a suitable decrease in the speeds of others. But the burden of having low temperature (low average molecular speed) is that you don't have a lot of room to decrease the speeds before hitting rock bottom, zero. The available range of possible molecular speeds is thus narrow, and so your freedom to rearrange the speeds is limited. By comparison, if the temperature is high, your game of musical chairs once again revs up: with a higher average, the range of molecular speeds—some larger than the average and some smaller—is much wider, providing greater latitude for mixing up the speeds while preserving the average. More rearrangements of the molecular speeds that all pretty much look the same means that higher temperature generally entails higher entropy.

Finally, pressure. The pressure of the steam on your skin or on the bathroom walls is due to the impact of streaming H_2O molecules that slam into these surfaces: each molecular impact exerts a tiny push, and so the greater the number of molecules the higher the pressure. For a given temperature and volume, pressure is thus determined by the total number of steam molecules in your bathroom, a quantity whose consequences for entropy can be worked out with the greatest of ease. Fewer H_2O molecules in your bathroom (you took a shorter shower) means fewer rearrangements are possible, and so entropy is lower; more H_2O molecules (you took a longer shower) means more rearrangements are possible, and so entropy is higher.

To summarize: Having fewer molecules, or having lower temperature, or filling a smaller volume results in lower entropy.

Having more molecules, or having higher temperature, or filling a larger volume results in higher entropy.

From this brief survey, let me underscore one way of thinking about entropy, lacking in precision but providing a useful rule of thumb. You should expect to encounter high-entropy states. Because such states can be realized by a great many different arrangements of the constituent particles, they're typical, pedestrian, easily configured, a dime a dozen. By contrast, if you encounter a low-entropy state it should command your attention. Low entropy means there are far fewer ways the given macrostate can be realized by its microscopic ingredients, and so such configurations are hard to come by, they're unusual, they're carefully arranged, they're rare. Step out of a long hot shower and find the steam uniformly spread throughout your bathroom: high entropy and totally unsurprising. Step out of a long hot shower and find the steam all clustered in a perfect little cube hovering in front of the mirror: low entropy and extraordinarily unusual. So unusual, in fact, that were you to encounter such a configuration you should be extremely skeptical of the explanation that you've simply come upon one of those unlikely things that on occasion happen. That *could* be the explanation. But I'd bet my life it isn't. Just as you'd suspect there's a reason beyond mere chance that a hundred pennies on your dining room table are all heads (such as someone judiciously flipped over each coin that landed tails), you should seek an explanation beyond mere chance for any low-entropy configurations you encounter.

This reasoning applies even to the seemingly mundane, like coming across an egg or an anthill or a mug. The orderly, crafted, low-entropy nature of these configurations calls out for an explanation. That the random motion of precisely the right particles could just happen to coalesce into an egg or an anthill or a mug is conceivable, but far-fetched. Instead, we're motivated to find more convincing explanations, and of course we don't have far to search: the egg and the anthill and the mug each arise from particular forms of life arranging the otherwise random configuration of particles in the environment to yield orderly structures. How life is able to produce such exquisite order is a theme we