ALICE AND BOB MEET THE WALL OF FIRE

THE BIGGEST IDEAS IN SCIENCE FROM *QUANTA*

EDITED BY

THOMAS LIN

FOREWORD BY **SEAN CARROLL**

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FOREWORD

Sean Carroll

Quanta has been a revelation.

All scientists are well aware that diplomatic relations across the border between science and journalism typically range from "wary" to "downright hostile." It's not that there is any natural antipathy between the groups, both of which largely consist of dedicated professionals pursuing an honorable craft. Scientists attempt to discover true things about the natural world and rely on journalists to spread the word of those discoveries to a wide audience; journalists hope to convey those discoveries in engaging and accurate ways and rely on scientists to help them understand and communicate. But the relevant sets of standards and incentives are different. Scientists lapse into jargon in an attempt to preserve precision, and they place enormous value on the precise attribution of credit; journalists want to tell a human story that will be compelling to nonscientists, and they are naturally drawn to the most dramatic angle that can be attached to any particular finding.

Thus, tension. Scientists find themselves insisting that the new way they have developed to slow down the speed of light through a crystal does not, in fact, open any potential routes to warp drive and/or time travel. Journalists have to gently explain that their four-paragraph story won't actually be able to list all 12 coauthors of the original study, nor will there be room to explain the finer points of adiabatic softening. Scientists reluctantly go along with this, only to be aghast when two of the four paragraphs in the final article are devoted to the whimsical antics of the new puppy one of the grad students was bringing to the lab. These are the sacrifices we make for the sake of a human-interest angle.

Quanta was immediately, recognizably, a different kind of science magazine. It explains the real discoveries and speculations at the cutting edge, without implying that they'll make science fiction come true. It lets interesting science be interesting science. I've seen my colleagues' eyes light up when

Quanta is mentioned. "Oh, yeah, that magazine is amazing. They actually talk about science for real!"

It has also made an impact among journalists. I remember conversations with some of my writer friends along the lines of, "I'm really confused about what *Quanta* is looking for. I found a great anecdote about this puppy in a lab, but they seem to care more about what the lab is actually doing. That can't be right, can it?" (The details are entirely fabricated, but the spirit of the conversation is accurate.)

And the *Quanta* approach will, I predict, make an impact on you as you read the pieces in this collection. It's not that the stories are dry or devoid of human interest—quite the contrary. Scientists are people, and their hopes and fears come through vividly in these accounts. But the science is always paramount. And *Quanta* doesn't apologize for that.

Such science it is! I'll confess my bias here, as this collection shines a spotlight on the kind of challenging, speculative, cutting-edge physics that is my own primary interest. When reading through these stories, I get the warm feeling that these are my people.

It's an interesting time for fundamental physics. We have theories of surpassing rigor and beauty that also pass every experimental test—quantum mechanics, Einstein's general relativity for gravity, the Standard Model of particle physics and the Hot Big Bang cosmological model. You'd think we would be happy. But at the same time, we know that these theories are not the final story. They don't play well together, and they leave a number of crucial questions unanswered. How should we move forward in the absence of direct, actionable experimental clues?

In cosmology, researchers have become increasingly intrigued by the notion that we live in a multiverse. That's not quite as philosophical as it sounds. What cosmologists actually mean by a "multiverse" is really a single universe, but one composed of multiple mutually inaccessible regions, in which the conditions are very different from those of all the others. It's not a dorm-room fantasy; this conception of a multiverse arises naturally from inflationary cosmology and string theory, two of the most popular (though still speculative) ideas on the fundamental physics market today.

In these pages you'll read why physicists have been led to contemplate such extreme possibilities. It's not simply that cosmologists got bored and started positing a billion other universes; there are features of our universe, here and now, observed in the lab, that might best be explained if we imagine that we live in just one of a large ensemble of universes. What's more, you'll come to appreciate that our apparent inability to observe a multiverse might not be as cut-and-dried as it seems. This is how science progresses: Researchers take on a tough problem, propose some outlandish-sounding solutions and then work to wrestle those grandiose ideas into a down-and-dirty confrontation with the data.

Not everyone is happy with the multiverse idea, of course. Plenty of working scientists are concerned that the concept is a step too far away from the real work of science, venturing into a realm of unfettered speculation, and the tensions are well documented here. Take a peek inside a gathering of some of the world's brightest minds, where banners are raised in a "battle for the heart and soul of physics." (Human interest!)

Besides the structure of the universe as a whole, a major preoccupation of modern physics is the nature of space-time. You might think this was figured out a century back, when Einstein put forward his general theory of relativity, according to which space and time are unified into a dynamical, four-dimensional space-time whose twists and turns are observable to us as the force of gravity. That seems to be true at the "classical" level—the setup for physics worked out by Isaac Newton centuries ago, in which objects have definite positions and velocities. But now we know about quantum mechanics, which describes the world very differently. According to quantum mechanics, the observable world doesn't march forward with clockwork predictability; the best we can do in any particular situation is to calculate the probability of observing various possible outcomes of an experiment.

The problem—and it's a big one—is that this quantum approach has not yet been reconciled with the curved space-time of general relativity. That's the issue of quantum gravity, which forms a major theme of the pieces collected here. In the title piece, "Alice and Bob Meet the Wall of Fire," we are introduced to the firewall paradox: According to controversial recent research, quantum mechanics implies that observers falling into a black hole will be incinerated by a wall of fire, rather than ultimately being pulled apart by the gravitational field. This distasteful conclusion has led to some outlandish proposed solutions, up to and including the notion that particles that share quantum entanglement may also be associated with wormholes in space-time. Entanglement, indeed, may ultimately be responsible for the existence of space-time itself.

All this talk of entanglement reminds us of a lurking worry when we gird our loins to tackle the difficult problem of quantum gravity: If we're honest about it, we don't really understand quantum mechanics itself, even without dragging gravity into the picture. There's no question that we can *use* quantum mechanics, both to make staggeringly precise predictions and to uncover the hidden beauty in the dynamics of particles and fields. But ask physicists what quantum mechanics actually *is* and they'll look nervous and discomfited. People have ideas, of course, some of which you will meet here: Maybe they will find hidden variables like the kind Einstein and others dreamed of long ago, or perhaps they can build the entire edifice from scratch.

Or perhaps the secret to reconciling quantum theory with space-time isn't a better understanding of the quantum, but a better understanding of time. Maybe quantum effects are crucial to understanding the prosaic-seeming question of why time moves forward and not backward. Or, even more dramatically, perhaps entanglement is at the heart of what time itself really is.

All of this might seem like an overabundance of *perhapses* and *maybes*. Isn't science supposed to be a repository of firm, established truths about nature?

Eventually, yes. But the process of getting there is messy and unpredictable, full of false starts and discarded hypotheses. The focus in *Quanta* is on science at the cutting edge, where things are never simple. You can see the dialectical process in action in "A Debate over the Physics of Time." It's an up-close view of physicists and philosophers coming together to exchange ideas and occasionally shout at each other ("I'm sick and tired of this block universe!"—yes, we really talk like that).

The science in this book is by no means confined to physics. Among all the sciences, physics seems hard because it is actually quite simple. That is, we can take a basic system like a rocking pendulum or a planet orbiting the sun and explain more or less exactly how it behaves. Having accomplished this, we move on to harder things—curved space-time, subatomic particles, the origin of the universe itself. A lot of the low-hanging fruit has already been picked, leaving cutting-edge research to concern itself with some extremely ambitious ideas.

The rest of science is messier and, correspondingly, harder. In biology, we can take a basic system like an earthworm or even a bacterium, and—well, suffice it to say, we are nowhere close to offering up an exact description of how these things work. Physics leans heavily on the fact that we can often ignore large sets of complications (friction, noise, air resistance) and still get a pretty good answer. In the wild and woolly world of biological complexity, all of the pieces matter.

In *Quanta*'s takes on biology and life, a couple of themes emerge. One, unsurprisingly, is Darwin's theory of evolution by natural selection. Perhaps more surprising is how much richer the paradigm has become as scientists continue to tinker with it. Darwin himself, of course, knew nothing of microbiology or DNA, and modern scientists are racing to improve our understanding of how genetic information is passed down through generations. And in a game-changing discovery whose ultimate implications are still far from understood, a tool called CRISPR promises to allow us to dig into the basic letters of the genetic code to edit DNA directly. The CRISPR piece surely won't be the last story about gene editing to appear in *Quanta*—it holds the promise to revolutionize medicine and perhaps exert profound changes on what it means to be human.

Another theme is the origin of life and its complexity. One might worry that life seems paradoxical when considered in the broader sweep of cosmic history. According to the second law of thermodynamics, entropy (a measure of disorder or randomness) increases over time; how, then, did something as orderly and nonrandom as living beings come into existence? An intriguing modern view is that this isn't a paradox at all, but rather a natural connection: Perhaps life began not despite the increase in entropy but because of it. After all, although an individual organism may be intricately ordered, it will inevitably increase the entropy of the universe by the simple fact that it metabolizes food to stay alive. But we would still like a detailed, historical understanding of why life became complex in the particular ways that it did—it seems possible that this is a process that happens even if natural selection doesn't nudge us in that direction. Even structures as specific as neurons may have independently come into existence more than once.

Among all the leaves on the tree of life, the one that many of us are most curious about is humanity itself. Evolution, needless to say, plays a central role in explaining how we became who we are. *Homo sapiens* didn't burst into existence fully formed, like Athena from the brow of Zeus; our plucky ability to thrive in a diverse set of environments may be a legacy of the genes we inherited from our prehistoric ancestors. What truly set us apart, of course, was the "brain boom" that began 3 million years ago, when the human brain began to almost quadruple in size in comparison to that of its predecessors.

The quest to understand how that brain works will doubtless keep scientists occupied for many generations to come. One step is simply to understand how our mind's various capacities are assembled over the course of our early lives. It happens rapidly: Within six months after birth, an infant's brain has the same basic organization as that of an adult. Once it's assembled, as marvelous as it is, the brain falls far short of being a perfectly rational machine. If you feel a twinge of guilt at your inability to resist another slice of pizza or an extra scoop of ice cream, take solace in the fact that these tendencies are simply part of a neurological optimization strategy, as the brain saves its energy for more important tasks. Even something as fundamentally human as the tendency to get lonely can be given a scientific explanation, as a type of incentive to inspire us to social cooperation.

Brains matter because we use them to think. What is this "thinking" on which we place such value? For many years, scientists and philosophers have speculated that something akin to human thought could also conceivably take place inside a mechanical device such as a computer. We may be entering the first generation in which this prediction will be put to the test. Along some fronts, progress has been impressive: Model "brains" built from tiny atomic switches can learn new things, and artificial agents can display something recognizable as curiosity. Computers nowadays handily defeat the world's best chess players, and recent victories at the even more complex game of Go hint at the development of something that might even be labeled "intuition." A great deal of excitement has accompanied the rise of "deep learning," a method of allowing networks of artificial neurons to train themselves to recognize and manipulate high-level concepts. Despite some initial successes, there is a lingering worry that after such a network trains itself, its creators can't understand how it is actually doing what it does. So begins the quest to construct a theory of deep learning.

Surveying the scope and depth of this collection of articles, one cannot help but feel optimistic about the future—the future of not only science but also science journalism.

In neither case is the optimism pure and unadulterated. On the science side, we must always be prepared for those times when our experiments don't give us the answers we were hoping for. That's happened in recent years in particle physics, where the lack of new particles to be found beyond the Higgs boson has left physicists scratching their heads and wondering whether there's a fundamental mistake in how we've been thinking about nature. But for every disappointment, there are multiple triumphs: The detection of gravitational waves from merging black holes and neutron stars has sparked a revolution that promises to energize astrophysics for years to come. Whatever our frustrations may be with the current pace of scientific progress, we must remember that it's not the universe's job to keep us happy; it's our job to do the best we can at uncovering its secrets.

At the same time, science journalism has suffered from the general downturn in traditional media coverage, including an elimination of many staff jobs at newspapers and magazines. Reason for hope is to be found in a broadening ecosystem as a wide variety of outlets have sprung into existence. Within this group, *Quanta* is a guiding light, providing other media with an example of science writing at its best.

In a sense, these stories are a snapshot of a moment in time; the thing about the cutting edge is that it keeps moving. Some of the scientific ideas explored here will fade away or be dramatically ruled out whereas others will become absolutely central to how we think about the universe. However, the ideal of communicating science by taking it seriously, by wrestling with difficult concepts and explaining them in honest, clear language—that is here to stay.

INTRODUCTION

Thomas Lin
Quanta Magazine editor in chief

It's hard to beat a good science or math story.

Take the events of July 4, 2012. That morning, scientists at the world's biggest physics experiment, the Large Hadron Collider near Geneva, Switzerland, made the biggest announcement of their lives. After investing 20 years in the effort to design and construct the LHC, only to suffer a demoralizing malfunction soon after it went online in 2008, they had finally discovered the Higgs boson, a particle without which life and the universe as we know it could not exist. The next year, Peter W. Higgs and François Englert, whose theoretical work in the 1960s predicted the Higgs particle, won the Nobel Prize in Physics.

A year later, the documentary film *Particle Fever* chronicled the hopes and dreams of the thousands of researchers behind the Higgs discovery. In one of my favorite scenes, the theorist David Kaplan is shown in 2008 explaining to a packed lecture hall why they built what the experimentalist Monica Dunford calls "a five-story Swiss watch." Unmoved by Kaplan's talk, an economist demands to know what people stand to gain from the multibillion-dollar experiment: "What's the economic return? How do you justify all this?"

"I have no idea," Kaplan answers bluntly. He must get this question all the time. Patiently, he explains that big breakthroughs in basic science "occur at a level where you're not asking, 'What is the economic gain?' You're asking, 'What do we not know, and where can we make progress?'" In their purest forms, science and mathematics are not about engineering practical applications or cashing in on them, though those things often do happen later, sometimes much later. They're about learning something you didn't know before.

"So, what is the LHC good for?" Kaplan asks the economist, setting up the death blow: "It could be nothing, other than just—understanding everything."

As it happens, this book picks up where *Particle Fever* leaves off in telling the story of the quest to understand everything. The renowned theoretical physicist Nima Arkani-Hamed has described such efforts in fundamental physics as "trying to understand, in the simplest possible way, the smallest set of basic principles from which everything else in principle follows." The fewer the assumptions, the approximations, the contortions—or so the thinking goes—the closer we are to the truth. The Higgs boson has been discovered and the Standard Model of particle physics is now complete. The problem is, absent new particles beyond the Standard Model, the universe doesn't make sense. How, then, are we to make sense of it?

In *Alice and Bob Meet the Wall of Fire: The Biggest Ideas in Science from* Quanta, and *The Prime Number Conspiracy: The Biggest Ideas in Math from* Quanta, we join some of the greatest scientific and mathematical minds as they test the limits of human knowledge. The stories presented in these two companion volumes reveal efforts over the past five years or so to untangle the mysteries of the universe—its origins and basic laws, its contents big and small, its profoundly complex living inhabitants—and to unlock the universal language of nature. They penetrate the big questions and uncover some of the best ideas and theories for understanding our physical, biotic and logical worlds. Meanwhile, they illuminate the essential issues under debate as well as the obstacles hindering further progress.

In selecting and editing *Quanta Magazine* articles for these volumes, I tried to venture beyond the usual mixtape format of "best of" anthologies and greatest hits compilations. Instead, I wanted to send readers on breathtaking intellectual journeys to the bleeding edge of discovery strapped to the narrative rocket of humanity's never-ending pursuit of knowledge. But what might those excursions actually look like? These nonfiction adventures, it turns out, explore core questions about the essence of prime numbers, whether our universe is "natural," the natures of time and infinity, our strange quantum reality, whether space-time is fundamental or emergent, the insides and outsides of black holes, the origin and evolution of life, what makes us human, the hopes for and limitations of computing, the role of mathematics in science and society, and just where these questions are taking us. The stories in these books reveal how cutting-edge research is done—how the productive tension between theory, experiment and mathematical intuition, through triumphs, failures and null results, cuts a path forward.

What is *Quanta*? Albert Einstein called photons "quanta of light." *Quanta Magazine* strives to illuminate the dark recesses in science and mathematics where some of the most provocative and fundamental ideas are cultivated out of public view. Not that anyone is trying to hide them. The work hides in plain sight at highly technical conferences and workshops, on the preprint site arxiv.org and in impenetrable academic journals. These are not easy subjects to understand, even for experts in adjacent fields, so it's not surprising that only Higgs-level discoveries are widely covered by the popular press.

The story of *Quanta* began in 2012, just weeks after the Higgs announcement. With the news industry still reeling from the 2008 financial crisis and secular declines in print advertising, I had the not-so-brilliant idea to start a science magazine. The magazine I envisioned would apply the best editorial standards of publications like the *New York Times* and the *New Yorker*, but its coverage would differ radically from that of existing news outlets. For one thing, it wouldn't report on anything you might actually find useful. This magazine would not publish health or medical news or breathless coverage of the latest technological breakthroughs. There would be no advice on which foods or vitamins to consume or avoid, which exercises to wedge into your day, which gadgets are must-buys. No stories about crumbling infrastructure or awesome feats of engineering. It wouldn't even keep you updated about the latest NASA mission, exoplanet find or SpaceX rocket launch. There's nothing wrong with any of this, of course. When accurately reported, deftly written, and carefully fact checked, it's "news you can use." But I had other ideas. I wanted a science magazine that helps us achieve escape velocity beyond our own small worlds but is otherwise useless in the way the LHC is useless. This useless magazine became *Quanta*.

My colleagues and I also treat our readers differently. We don't protect them from the central concepts or from the process of how new ideas come to be. Indeed, the ridiculously difficult science and math problems and the manner in which an individual or collaboration makes progress serve as the very conflicts and resolutions that drive *Quanta* narratives. We avoid jargon, but we don't protect readers from the science itself. We trust readers, whether they have a science background or not, to be intellectually curious enough to want to know more, so we give you more.

Like the magazine, this book is for anyone who wants to understand how nature works, what the universe is made of, and how life got its start and evolved into its myriad forms. It's for curiosity seekers who want a front-row seat for breakthroughs to the biggest mathematical puzzles and whose idea of fun is to witness the expansion of our mathematical universe.

If I may offer an adaptation of Shel Silverstein's famous lyric invitation (my sincere apologies to the late Mr. Silverstein):

> If you are a dreamer, come in,
> If you are a dreamer, a thinker, a curiosity seeker,
> A theorizer, an experimenter, a *mathematiker* …
> If you're a tinkerer, come fill my beaker
> For we have some mind-bendin' puzzles to examine.
> Come in!
> Come in!

I

WHY DOESN'T OUR UNIVERSE MAKE SENSE?

IS NATURE UNNATURAL?

Natalie Wolchover

On an overcast afternoon in late April 2013, physics professors and students crowded into a wood-paneled lecture hall at Columbia University for a talk by Nima Arkani-Hamed, a high-profile theorist visiting from the Institute for Advanced Study in nearby Princeton, New Jersey. With his dark, shoulder-length hair shoved behind his ears, Arkani-Hamed laid out the dual, seemingly contradictory implications of recent experimental results at the Large Hadron Collider in Europe.

“The universe is inevitable,” he declared. “The universe is impossible.”

The spectacular discovery of the Higgs boson in July 2012 confirmed a nearly 50-year-old theory of how elementary particles acquire mass, which enables them to form big structures such as galaxies and humans. “The fact that it was seen more or less where we expected to find it is a triumph for experiment, it’s a triumph for theory, and it’s an indication that physics works,” Arkani-Hamed told the crowd.

However, in order for the Higgs boson to make sense with the mass (or equivalent energy) it was determined to have, the LHC needed to find a swarm of other particles, too. None turned up.

With the discovery of only one particle, the LHC experiments deepened a profound problem in physics that had been brewing for decades. Modern equations seem to capture reality with breathtaking accuracy, correctly predicting the values of many constants of nature and the existence of particles like the Higgs. Yet a few constants—including the mass of the Higgs boson—are exponentially different from what these trusted laws indicate they should be, in ways that would rule out any chance of life, unless the universe is shaped by inexplicable fine-tunings and cancellations.

In peril is the notion of “naturalness,” Albert Einstein’s dream that the laws of nature are sublimely beautiful, inevitable and self-contained. Without it, physicists face the harsh prospect that those laws are just an arbitrary, messy outcome of random fluctuations in the fabric of space and time.

In papers, talks and interviews, Arkani-Hamed and many other top physicists are confronting the possibility that the universe might be unnatural. (There is wide disagreement, however, about what it would take to prove it.)

"Ten or 20 years ago, I was a firm believer in naturalness," said Nathan Seiberg, a theoretical physicist at the Institute, where Einstein taught from 1933 until his death in 1955. "Now I'm not so sure. My hope is there's still something we haven't thought about, some other mechanism that would explain all these things. But I don't see what it could be."

Physicists reason that if the universe is unnatural, with extremely unlikely fundamental constants that make life possible, then an enormous number of universes must exist for our improbable case to have been realized. Otherwise, why should we be so lucky? Unnaturalness would give a huge lift to the multiverse hypothesis, which holds that our universe is one bubble in an infinite and inaccessible foam. According to a popular but polarizing framework called string theory, the number of possible types of universes that can bubble up in a multiverse is around 10^{500}. In a few of them, chance cancellations would produce the strange constants we observe.

In such a picture, not everything about this universe is inevitable, rendering it unpredictable. Edward Witten, a string theorist at the Institute, said by email, "I would be happy personally if the multiverse interpretation is not correct, in part because it potentially limits our ability to understand the laws of physics. But none of us were consulted when the universe was created."

"Some people hate it," said Raphael Bousso, a physicist at the University of California at Berkeley who helped develop the multiverse scenario. "But I just don't think we can analyze it on an emotional basis. It's a logical possibility that is increasingly favored in the absence of naturalness at the LHC."

What the LHC does or doesn't discover in future runs is likely to lend support to one of two possibilities: Either we live in an overcomplicated but stand-alone universe, or we inhabit an atypical bubble in a multiverse. "We will be a lot smarter five or 10 years from today because of the LHC," Seiberg said. "So that's exciting. This is within reach."

COSMIC COINCIDENCE

Einstein once wrote that for a scientist, "religious feeling takes the form of a rapturous amazement at the harmony of natural law" and that "this feeling is the guiding principle of his life and work." Indeed, throughout the 20th century, the deep-seated belief that the laws of nature are harmonious—a belief in "naturalness"—has proven a reliable guide for discovering truth.

"Naturalness has a track record," Arkani-Hamed told *Quanta*. In practice, it is the requirement that the physical constants (particle masses and other fixed properties of the universe) emerge directly from the laws of physics, rather than resulting from improbable cancellations. Time and again, whenever a constant appeared fine-tuned, as if its initial value had been magically dialed to offset other effects, physicists suspected they were missing something. They would seek and inevitably find some particle or feature that materially dialed the constant, obviating a fine-tuned cancellation.

This time, the self-healing powers of the universe seem to be failing. The Higgs boson has a mass of 126 giga-electron-volts, but interactions with the other known particles should add about 10,000,000,000,000,000,000 giga-electron-volts to its mass. This implies that the Higgs' "bare mass," or starting value before other particles affect it, just so happens to be the negative of that astronomical number, resulting in a near-perfect cancellation that leaves just a hint of Higgs behind: 126 giga-electron-volts.

Physicists have gone through three generations of particle accelerators searching for new particles, posited by a theory called supersymmetry, that would drive the Higgs mass down exactly as much as the known particles drive it up. But so far they've come up empty-handed.

At this point, even if new particles are found at the LHC, they will almost definitely be too heavy to influence the Higgs mass in quite the right way. Physicists disagree about whether this is acceptable in a natural, stand-alone universe. "Fine-tuned a little—maybe it just happens," said Lisa Randall, a professor at Harvard University. But in Arkani-Hamed's opinion, being "a little bit tuned is like being a little bit pregnant. It just doesn't exist."

If no new particles appear and the Higgs remains astronomically fine-tuned, then the multiverse hypothesis will stride into the limelight. "It doesn't mean it's right," said Bousso, a longtime supporter of the multiverse picture, "but it does mean it's the only game in town."

A few physicists—notably Joe Lykken of Fermi National Accelerator Laboratory in Batavia, Illinois, and Alessandro Strumia of the University of Pisa in Italy—see a third option. They say that physicists might be misgauging the effects of other particles on the Higgs mass and that when calculated differently, its mass appears natural. This "modified naturalness" falters when additional particles, such as the unknown constituents of dark matter, are included in calculations—but the same unorthodox path could yield other ideas.[1] "I don't want to advocate, but just to discuss the consequences," Strumia said during a 2013 talk at Brookhaven National Laboratory in Long Island, New York.

However, modified naturalness cannot fix an even bigger naturalness problem that exists in physics: the fact that the cosmos wasn't instantly annihilated by its own energy the moment after the Big Bang.

DARK DILEMMA

The energy built into the vacuum of space (known as vacuum energy, dark energy or the cosmological constant) is a baffling trillion trillion trillion trillion trillion trillion trillion trillion trillion trillion times smaller than what is calculated to be its natural, albeit self-destructive, value. No theory exists about what could naturally fix this gargantuan disparity. But it's clear that the cosmological constant has to be enormously fine-tuned to prevent the universe from rapidly exploding or collapsing to a point. It has to be fine-tuned in order for life to have a chance.

To explain this absurd bit of luck, the multiverse idea has been growing mainstream in cosmology circles over the past few decades. It got a credibility boost in 1987 when the Nobel Prize-winning physicist Steven Weinberg, now a professor at the University of Texas at Austin, calculated that the cosmological constant of our universe is expected in the multiverse scenario.[2] Of the possible universes capable of supporting life—the only ones that can be observed and contemplated in the first place—ours is among the least fine-tuned. "If the cosmological constant were much larger than the observed value, say by a factor of 10, then we would have no galaxies," explained Alexander Vilenkin, a cosmologist and multiverse theorist at Tufts University. "It's hard to imagine how life might exist in such a universe."

Most particle physicists hoped that a more testable explanation for the cosmological constant problem would be found. None has. Now, physicists say, the unnaturalness of the Higgs makes the unnaturalness of the cosmological constant more significant. Arkani-Hamed thinks the issues may even be related. "We don't have an understanding of a basic extraordinary fact about our universe," he said. "It is big and has big things in it."

The multiverse turned into slightly more than just a hand-waving argument in 2000, when Bousso and Joseph Polchinski, a professor of theoretical physics at the University of California at Santa Barbara, found a mechanism that could give rise to a panorama of parallel universes. String theory, a hypothetical "theory of everything" that regards particles as invisibly small vibrating lines, posits that space-time is 10-dimensional. At the human scale, we experience just three dimensions of space and one of time, but string theorists argue that six extra dimensions are tightly knotted at every point in the fabric of our 4-D reality. Bousso and Polchinski calculated that there are around 10^{500} different ways for those six dimensions to be knotted (all tying up varying amounts of energy), making an inconceivably vast and diverse array of universes possible.[3] In other words, naturalness is not required. There isn't a single, inevitable, perfect universe.

"It was definitely an aha-moment for me," Bousso said. But the paper sparked outrage.

"Particle physicists, especially string theorists, had this dream of predicting uniquely all the constants of nature," Bousso explained. "Everything would just come out of math and pi and twos [or other simple constants]. And we came in and said, 'Look, it's not going to happen, and there's a reason it's not going to happen. We're thinking about this in totally the wrong way.'"

LIFE IN A MULTIVERSE

The Big Bang, in the Bousso-Polchinski multiverse scenario, is a fluctuation. A compact, six-dimensional knot that makes up one stitch in the fabric of reality suddenly shape-shifts, releasing energy that forms a bubble of space and time. The properties of this new universe are determined by chance: the amount of energy unleashed during the fluctuation. The vast majority of universes that burst into being in this way are thick with vacuum energy; they either expand or collapse so quickly that life cannot arise in them. But some atypical universes, in which an improbable cancellation yields a tiny value for the cosmological constant, are much like ours.

In a paper posted in 2013 to the physics preprint website arXiv.org, Bousso and a Berkeley colleague, Lawrence Hall, argued that the Higgs mass makes sense in the multiverse scenario, too.[4] They found that bubble universes that contain enough visible matter (compared to dark matter) to support life most often have supersymmetric particles beyond the energy range of the LHC, and a fine-tuned Higgs boson. Similarly, other physicists showed in 1997 that if the Higgs boson were five times heavier than it is, this would suppress the formation of atoms other than hydrogen, resulting, by yet another means, in a lifeless universe.[5]

Despite these seemingly successful explanations, many physicists worry that there is little to be gained by adopting the multiverse worldview. Parallel universes cannot be tested for; worse, an unnatural universe resists understanding. "Without naturalness, we will lose the motivation to look for new physics," said Kfir Blum in 2013, when he was a physicist at the

Institute for Advanced Study. "We know it's there, but there is no robust argument for why we should find it." That sentiment is echoed again and again: "I would prefer the universe to be natural," Randall said.

But theories can grow on physicists. After spending more than a decade acclimating himself to the multiverse, Arkani-Hamed now finds it plausible—and a viable route to understanding the ways of our world. "The wonderful point, as far as I'm concerned, is basically any result at the LHC will steer us with different degrees of force down one of these divergent paths," he said. "This kind of choice is a very, very big deal."

Naturalness could pull through. Or it could be a false hope in a strange but comfortable pocket of the multiverse.

As Arkani-Hamed told the audience at Columbia University, "stay tuned."

ALICE AND BOB MEET THE WALL OF FIRE

Jennifer Ouellette

Alice and Bob, beloved characters of various thought experiments in quantum mechanics, are at a crossroads. The adventurous, rather reckless Alice jumps into a very large black hole, leaving a presumably forlorn Bob outside the event horizon—a black hole's point of no return, beyond which nothing, not even light, can escape.

Conventionally, physicists have assumed that if the black hole is large enough, Alice won't notice anything unusual as she crosses the horizon. In this scenario, colorfully dubbed "No Drama," the gravitational forces won't become extreme until she approaches a point inside the black hole called the singularity. There, the gravitational pull will be so much stronger on her feet than on her head that Alice will be "spaghettified."

Now a new hypothesis is giving poor Alice even more drama than she bargained for. If this alternative is correct, as the unsuspecting Alice crosses the event horizon, she will encounter a massive wall of fire that will incinerate her on the spot. As unfair as this seems for Alice, the scenario would also mean that at least one of three cherished notions in theoretical physics must be wrong.

When Alice's fiery fate was proposed in the summer of 2012, it set off heated debates among physicists, many of whom were highly skeptical. "My initial reaction was, 'You've got to be kidding,'" admitted Raphael Bousso. He thought a forceful counterargument would quickly emerge and put the matter to rest. Instead, after a flurry of papers debating the subject, he and his colleagues realized that this had the makings of a mighty fine paradox.

THE "MENU FROM HELL"

Paradoxes in physics have a way of clarifying key issues. At the heart of this particular puzzle lies a conflict between three fundamental postulates beloved by many physicists. The first, based on the equivalence principle of general relativity, leads to the No Drama scenario: Because Alice is in free fall as she crosses the horizon, and there is no difference between free fall and inertial motion, she shouldn't feel extreme effects of gravity. The second postulate is unitarity, the assumption, in keeping with a fundamental tenet of quantum mechanics, that information that falls into a black hole is not irretrievably lost. Lastly, there is what might be best described as "normality," namely, that physics works as expected far away from a black hole even if it breaks down at some point within the black hole—either at the singularity or at the event horizon.

Together, these concepts make up what Bousso ruefully calls "the menu from hell." To resolve the paradox, one of the three must be sacrificed, and nobody can agree on which one should get the ax.

Physicists don't lightly abandon time-honored postulates. That's why so many find the notion of a wall of fire downright noxious. "It is odious," John Preskill of the California Institute of Technology declared in December 2012 at an informal workshop organized by Stanford University's Leonard Susskind. For two days, 50 or so physicists engaged in a spirited brainstorming session, tossing out all manner of crazy ideas to try to resolve the paradox, punctuated by the rapid-fire *tap-tap-tap* of equations being scrawled on a blackboard. But despite the collective angst, even the firewall's fiercest detractors have yet to find a satisfactory solution to the conundrum.

According to the string theorist Joseph Polchinski, who spoke to *Quanta* soon after making the proposal and died in February 2018 of brain cancer, the simplest solution is that the equivalence principle breaks down at the event horizon, thereby giving rise to a firewall. Polchinski was a co-author of the paper that started it all, along with Ahmed Almheiri, Donald Marolf and James Sully—a group often referred to as "AMPS."[1] Even Polchinski thought the idea was a little crazy. It's a testament to the knottiness of the problem that a firewall is the least radical potential solution.

If there is an error in the firewall argument, the mistake is not obvious. That's the hallmark of a good scientific paradox. And it comes at a time when theorists are hungry for a new challenge: The Large Hadron Collider has failed to turn up any data hinting at exotic physics beyond the Standard Model. "In the absence of data, theorists thrive on paradox," Polchinski quipped.

If AMPS is wrong, according to Susskind, it is wrong in a really interesting way that will push physics forward, hopefully toward a robust theory of quantum gravity.[2] Black holes are interesting to physicists, after all, because both general relativity and quantum mechanics can apply, unlike in the rest of the universe, where objects are governed by quantum mechanics at the subatomic scale and by general relativity on the macroscale. The two "rule books" work well enough in their respective regimes, but physicists would love to combine them to shed light on anomalies like black holes and, by extension, the origins of the universe.

AN ENTANGLED PARADOX

The issues are complicated and subtle—if they were simple, there would be no paradox—but a large part of the AMPS argument hinges on the notion of monogamous quantum entanglement: You can only have one kind of entanglement at a time. AMPS argues that two different kinds of entanglement are needed in order for all three postulates on the "menu from hell" to be true. Since the rules of quantum mechanics don't allow you to have both entanglements, one of the three postulates must be sacrificed.

Entanglement—which Albert Einstein ridiculed as "spooky action at a distance"—is a well-known feature of quantum mechanics (in the thought experiment, Alice and Bob represent an entangled particle pair). When subatomic particles collide, they can become invisibly connected, though they may be physically separated. Even at a distance, they are inextricably interlinked and act like a single object. So knowledge about one partner can instantly reveal knowledge about the other. The catch is that you can only have one entanglement at a time.

Under classical physics, as Preskill explained on Caltech's Quantum Frontiers blog, Alice and Bob can both have copies of the same newspaper, which gives them access to the same information. Sharing this bond of sorts makes them "strongly correlated." A third person, "Carrie," can also buy a copy of that newspaper, which gives her equal access to the information it contains, thereby forging a correlation with Bob without weakening his correlation with Alice. In fact, any number of people can buy a copy of that same newspaper and become strongly correlated with one another.

But with quantum correlations, that is not the case. For Bob and Alice to be maximally entangled, their respective newspapers must have the same orientation, whether right side up, upside down or sideways. So long as the orientation is the same, Alice and Bob will have access to the same information. "Because there is just one way to read a classical newspaper and lots of ways to read a quantum newspaper, the quantum correlations are stronger than the classical ones," Preskill said. That makes it impossible for Bob to become as strongly entangled with Carrie as he is with Alice without sacrificing some of his entanglement with Alice.

This is problematic because there is more than one kind of entanglement associated with a black hole, and under the AMPS hypothesis, the two come into conflict. There is an entanglement between Alice, the in-falling observer, and Bob, the outside observer, which is needed to preserve No Drama. But there is also a second entanglement that emerged from another famous paradox in physics, one related to the question of whether information is lost in a black hole. In the 1970s, Stephen Hawking realized that black holes aren't completely black. While nothing might seem amiss to Alice as she crosses the event horizon, from Bob's perspective, the horizon would appear to be glowing like a lump of coal—a phenomenon now known as Hawking radiation.

This radiation results from virtual particle pairs popping out of the quantum vacuum near a black hole. Normally they would collide and annihilate into energy, but sometimes one of the pair is sucked into the black hole while the other escapes to the outside world. The mass of the black hole, which must decrease slightly to counter this effect and ensure that energy is still conserved, gradually winks out of existence. How fast it evaporates depends on the black hole's size: The bigger it is, the more slowly it evaporates.

Hawking assumed that once the radiation evaporated altogether, any information about the black hole's contents contained in that radiation would be lost. "Not only does God play dice, but he sometimes confuses us by throwing them where they can't be seen," he famously declared. He and the Caltech physicist Kip Thorne even made a bet with a dubious Preskill in the 1990s about about whether or not information is lost in a black hole. Preskill insisted that information must be conserved; Hawking and Thorne believed that information would be lost. Physicists eventually realized that it is possible to preserve the information at a cost: As the black hole evaporates, the Hawking radiation must become increasingly entangled with the area outside the event horizon. So when Bob observes that radiation, he can extract the information.

But what happens if Bob were to compare his information with Alice's after she has passed beyond the event horizon? "That would be disastrous," Bousso explained, "because Bob, the outside observer, is seeing the same information in the Hawking radiation, and if they could talk about it, that would be quantum Xeroxing, which is strictly forbidden in quantum mechanics."

Physicists, led by Susskind, declared that the discrepancy between these two viewpoints of the black hole is fine so long as it is impossible for Alice and Bob to share their respective information. This concept, called complementarity, simply holds that there is no direct contradiction because no single observer can ever be both inside and outside the event horizon. If Alice crosses the event horizon, sees a star inside that radius and wants to tell Bob about it, general relativity has ways of preventing her from doing so.

Susskind's argument that information could be recovered without resorting to quantum Xeroxing proved convincing enough that Hawking conceded his bet with Preskill in 2004, presenting the latter with a baseball encyclopedia from which, he said, "information can be retrieved at will." But perhaps Thorne, who refused to concede, was right to be stubborn.

Bousso thought complementarity would come to the rescue yet again to resolve the firewall paradox. He soon realized that it was insufficient. Complementarity is a theoretical concept developed to address a specific problem, namely, reconciling the two viewpoints of observers inside and outside the event horizon. But the firewall is just the tiniest bit outside the event horizon, giving Alice and Bob the same viewpoint, so complementarity won't resolve the paradox.

TOWARD QUANTUM GRAVITY

If they wish to get rid of the firewall and preserve No Drama, physicists need to find a new theoretical insight tailored to this unique situation or concede that perhaps Hawking was right all along, and information is indeed lost, meaning Preskill might have to return his encyclopedia. So it was surprising to find Preskill suggesting that his colleagues at the Stanford workshop at least reconsider the possibility of information loss. Although we don't know how to make sense of quantum mechanics without unitarity, "that doesn't mean it can't be done," he said. "Look in the mirror and ask yourself: Would I bet my life on unitarity?"

Polchinski argued persuasively in 2012 that you need Alice and Bob to be entangled to preserve No Drama, and you need the Hawking radiation to be entangled with the area outside the event horizon to conserve quantum information. But you can't have both. If you sacrifice the entanglement of the Hawking radiation with the area outside the event horizon, you lose information. If you sacrifice the entanglement of Alice and Bob, you get a firewall.

"Quantum mechanics doesn't allow both to be there," Polchinski said. "If you lose the entanglement between the in-falling (Alice) and the outgoing (Bob) observers, it means you've put some kind of sharp kink into the quantum state right at the horizon. You've broken a bond, in some sense, and that broken bond requires energy. This tells us the firewall has to be there."

That consequence arises from the fact that entanglement between the area outside the event horizon and the Hawking radiation must increase as the black hole evaporates. When roughly half the mass has radiated away, the black hole is maximally entangled and essentially experiences a midlife crisis. Preskill explained: “It’s as if the singularity, which we expected to find deep inside the black hole, has crept right up to the event horizon when the black hole is old.” And the result of this collision between the singularity and the event horizon is the dreaded firewall.

The mental image of a singularity migrating from deep within a black hole to the event horizon provoked at least one exasperated outburst during the Stanford workshop, a reaction Bousso finds understandable.[3] “We should be upset,” he said. “This is a terrible blow to general relativity.”

Yet for all his skepticism about firewalls, he is thrilled to be part of the debate. “This is probably the most exciting thing that’s happened to me since I entered physics,” he said. “It’s certainly the nicest paradox that’s come my way, and I’m excited to be working on it.”

Alice’s death by firewall seems destined to join the ranks of classic thought experiments in physics. The more physicists learn about quantum gravity, the more different it appears to be from our current picture of how the universe works, forcing them to sacrifice one cherished belief after another on the altar of scientific progress. Now they must choose to sacrifice either unitarity or No Drama, or undertake a radical modification of quantum field theory. Or maybe it’s all just a horrible mistake. Any way you slice it, physicists are bound to learn something new.

WORMHOLES UNTANGLE A BLACK HOLE PARADOX

K. C. Cole

One hundred years after Albert Einstein developed his general theory of relativity, physicists are still stuck with perhaps the biggest incompatibility problem in the universe. The smoothly warped space-time landscape that Einstein described is like a painting by Salvador Dalí—seamless, unbroken, geometric. But the quantum particles that occupy this space are more like something from Georges Seurat: pointillist, discrete, described by probabilities. At their core, the two descriptions contradict each other. Yet a bold new strain of thinking suggests that quantum correlations between specks of impressionist paint actually create not just Dalí's landscape, but the canvases that both sit on, as well as the three-dimensional space around them. And Einstein, as he so often does, sits right in the center of it all, still turning things upside-down from beyond the grave.

Like initials carved in a tree, ER = EPR, as the new idea is known, is a shorthand that joins two ideas proposed by Einstein in 1935. One involved the paradox implied by what he called "spooky action at a distance" between quantum particles (the EPR paradox, named for its authors, Einstein, Boris Podolsky and Nathan Rosen). The other showed how two black holes could be connected through far reaches of space through "wormholes" (ER, for Einstein-Rosen bridges). At the time that Einstein put forth these ideas—and for most of the eight decades since—they were thought to be entirely unrelated.

But if ER = EPR is correct, the ideas aren't disconnected—they're two manifestations of the same thing. And this underlying connectedness would form the foundation of all space-time. Quantum entanglement—the action at a distance that so troubled Einstein—could be creating the "spatial connectivity" that "sews space together," according to Leonard Susskind, a physicist at Stanford University and one of the idea's main architects. Without these connections, all of space would "atomize," according to Juan Maldacena, a physicist at the Institute for Advanced Study in Princeton, New Jersey, who developed the idea together with Susskind. "In other words, the solid and reliable structure of space-time is due to the ghostly features of entanglement," he said. What's more, ER = EPR has the potential to address how gravity fits together with quantum mechanics.

Not everyone's buying it, of course (nor should they; the idea is in "its infancy," said Susskind). Joseph Polchinski, whose own stunning paradox about firewalls in the throats of black holes triggered the latest advances, was cautious, but intrigued, when asked about it in 2015. "I don't know where it's going," he said, "but it's a fun time right now."

THE BLACK HOLE WARS

The road that led to ER = EPR is a Möbius strip of tangled twists and turns that folds back on itself, like a drawing by M. C. Escher.

A fair place to start might be quantum entanglement. If two quantum particles are entangled, they become, in effect, two parts of a single unit. What happens to one entangled particle happens to the other, no matter how far apart they are.

Maldacena sometimes uses a pair of gloves as an analogy: If you come upon the right-handed glove, you instantaneously know the other is left-handed. There's nothing spooky about that. But in the quantum version, both gloves are actually left- and right-handed (and everything in between) up until the moment you observe them. Spookier still, the left-handed glove doesn't become left until you observe the right-handed one—at which moment both instantly gain a definite handedness.

Entanglement played a key role in Stephen Hawking's 1974 discovery that black holes could evaporate. This, too, involved entangled pairs of particles. Throughout space, short-lived "virtual" particles of matter and antimatter continually pop into and out of existence. Hawking realized that if one particle fell into a black hole and the other escaped, the hole would emit radiation, glowing like a dying ember. Given enough time, the hole would evaporate into nothing, raising the question of what happened to the information content of the stuff that fell into it.

But the rules of quantum mechanics forbid the complete destruction of information. (Hopelessly scrambling information is another story, which is why documents can be burned and hard drives smashed. There's nothing in the laws of physics that prevents the information lost in a book's smoke and ashes from being reconstructed, at least in principle.) So the question became: Would the information that originally went into the black hole just get scrambled? Or would it be truly lost? The arguments set off what Susskind called the "black hole wars," which have generated enough stories to fill many books. (Susskind's was subtitled "My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics.")

Eventually Susskind—in a discovery that shocked even him—realized (with Gerard 't Hooft) that all the information that fell down the hole was actually trapped on the black hole's two-dimensional event horizon, the surface that marks the point of no return. The horizon encoded everything inside, like a hologram. It was as if the bits needed to re-create your house and everything in it could fit on the walls. The information wasn't lost—it was scrambled and stored out of reach.

Susskind continued to work on the idea with Maldacena, whom Susskind calls "the master," and others. Holography began to be used not just to understand black holes, but any region of space that can be described by its boundary. Over the past decade or so, the seemingly crazy idea that space is a kind of hologram has become rather humdrum, a tool of modern physics used in everything from cosmology to condensed matter. "One of the things that happens to scientific ideas is they often go from wild conjecture to reasonable conjecture to working tools," Susskind said. "It's gotten routine."

Holography was concerned with what happens on boundaries, including black hole horizons. That left open the question of what goes on in the interiors, said Susskind, and answers to that "were all over the map." After all, since no information could ever escape from inside a black hole's horizon, the laws of physics prevented scientists from ever directly testing what was going on inside.

Then in 2012 Polchinski, along with Ahmed Almheiri, Donald Marolf and James Sully, all of them at the time at Santa Barbara, came up with an insight so startling it basically said to physicists: Hold everything. We know nothing.

The so-called AMPS paper (after its authors' initials) presented a doozy of an entanglement paradox—one so stark it implied that black holes might not, in effect, even have insides, for a "firewall" just inside the horizon would fry anyone or anything attempting to find out its secrets.[1]

The AMPS paper became a "real trigger," said Stephen Shenker, a physicist at Stanford, and "cast in sharp relief" just how much was not understood. Of course, physicists love such paradoxes, because they're fertile ground for discovery.

Both Susskind and Maldacena got on it immediately. They'd been thinking about entanglement and wormholes, and both were inspired by the work of Mark Van Raamsdonk, a physicist at the University of British Columbia in Vancouver, who had conducted a pivotal thought experiment suggesting that entanglement and space-time are intimately related.

Marolf, who co-authored a paper describing wormholes with more than two ends.[4] ER = EPR works in very specific situations, he said, but AMPS argues that the firewall presents a much broader challenge.

Like Polchinski and others, Marolf worried that ER = EPR modifies standard quantum mechanics. “A lot of people are really interested in the ER = EPR conjecture,” said Marolf. “But there’s a sense that no one but Lenny and Juan really understand what it is.” Still, “it’s an interesting time to be in the field.”

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