MÖBIUS STRIP

WRITE SCIENCE.

ATLAS SCIENCE WRITING WORKSHOP

HANDOUTS FOR THE

ADVANCED SESSION

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BOOKS: FICTION

BOOKS: NON-FICTION

HTTP://THEOATMEAL.COM/COMICS/BELIEVE

A few years ago

at the University of Southern California's *Brain and Creativity Institute*, a study was conducted where participants were placed into a MRI machine.

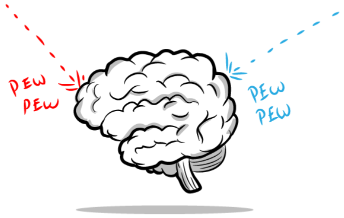
Once inside, they were presented with counterarguments to strongly held political beliefs.

A few examples:

"Laws restricting gun ownership should be made more restrictive."

"Gay marriage should not be legalized."

As participants were read these counterarguments, various parts of their brains were scanned for activity.



What the study revealed was that the same part of the brain that responds to a PHYSICAL threat responds to an INTELLECTUAL one.

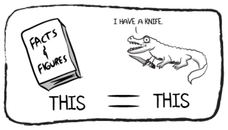
This area of the brain is known as the

amygdala,

and it's the emotional core of your mind.

Unfortunately,

it makes us biologically wired to react to threatening information the same way we'd react to being attacked by a predator.



From an evolutionary standpoint, it makes sense.

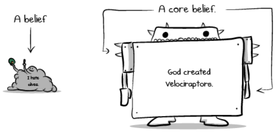
If you were a caveman and another caveman threw a boulder at your head, you wouldn't react by logically debating the pros and cons of getting brained.

Core beliefs

are the beliefs which people cherish the most deeply.

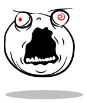
They usually develop from childhood and are compounded by life experiences.

Core beliefs are inflexible, rigid, and incredibly sensitive to being challenged.



When I told you that George Washington's dentures were made from animal bones, it probably didn't ruffle many feathers.

But when I suggested they were made from slave teeth, I'm guessing it caused strife with some of you.



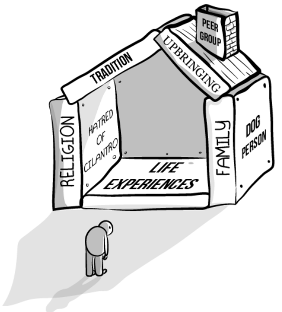
There are obvious cultural reasons for this; slavery is a sensitive, hot-button issue.

But there are biological reasons as well: the amygdala of your brain is screaming "BATTLE STATIONS."

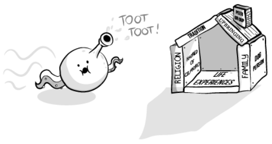
Some of you may have held a worldview that George Washington was a patriot and a hero. By presenting negative information about him, it challenged that worldview.

Your brain loves consistency. It builds a worldview like we build a house.

It has a foundation and a frame and windows and doors and it knows exactly how everything fits together.

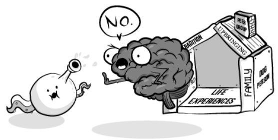


If new piece is introduced and it doesn't fit,

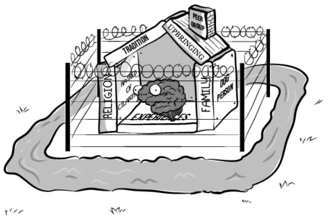


the whole house falls apart.

Your brain protects you by rejecting that piece.



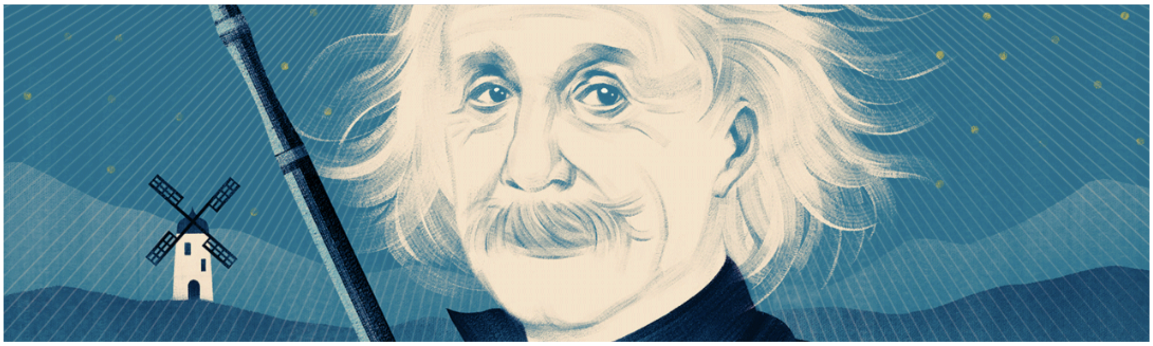
It then builds a fence and a moat and refuses to let in any visitors.



This is why we have the backfire effect. It's a biological way of protecting a worldview.

Just remember that your worldview isn't a perfect house that was built to last forever.

It's a cheap condo, and over time most of it will turn to shit.



MATTER | PHYSICS

When Einstein Tilted at Windmills

The young physicist's quest to prove the theories of Ernst Mach.

BY AMANDA GEFTER
ILLUSTRATION BY JASU HU
DECEMBER 1, 2016

When they met, Einstein wasn't *Einstein* yet. He was just Albert Einstein, a kid, about 17, with a dark cloud of teenage angst and a violin. Michele Besso was older, 23, but a kindred spirit. Growing up in Trieste, Italy he had shown an impressive knack for mathematics, but he was kicked out of high school for insubordination and had to go live with his uncle in Rome. Einstein could relate. At the Swiss Polytechnic, where he was now a student, his professors resented his intellectual arrogance, and had begun locking him out of the library out of spite.

Their first encounter was on a Saturday night in Zurich, 1896. They were at Selina Caprotti's house by the lake for one of her music parties. Einstein was handsome—dark hair, moustache, soulful brown eyes. Besso was short with narrow, pointed features and a thick pile of coarse black hair on his head and chin. Einstein had a look of cool detachment. Besso had the look of a nervous mystic. As they chatted, Einstein learned that Besso worked at an electrical machinery factory; Besso learned that Einstein was studying physics. Perhaps they recognized something in each other then: They both wanted to get to the truth of things.

Besso would go on to become a sidekick, of sorts, to Einstein—a sounding board, as Einstein put it, "the best in Europe," asking the right questions that would inspire Einstein to find the right answers. At times, though, he would seem to be something more—a collaborator, perhaps, making suggestions, working through calculations.

At other times he'd be the perfect fool—a *schlemiel*, Einstein called him. Like the time Besso was sent on a job to inspect some newly installed power lines on the outskirts of Milan but missed his train and then forgot to go the following day. On the third day he finally made it to his destination, but by that time he'd completely forgotten what he was supposed to be doing there in the first place. He sent a postcard to his boss: "Instructions should be wired."

If Besso never seemed to know quite what he was doing, it wasn't for a lack of smarts. "The great strength of Besso resides in his intelligence," Einstein would write, "which is out of the ordinary, and in his endless devotion to both his moral and professional obligations; his weakness is his truly insufficient spirit of decision. This explains why his successes in life do not match up with his brilliant aptitudes and with his extraordinary scientific and technical knowledge."

Still other times, Besso would play the role of Einstein's conscience—urging him to work things out with his future wife, Mileva, or to be a better father to his sons. Besso took care of those sons on Einstein's behalf when Mileva was sick. "Nobody else is so close to me, nobody knows me so well," Einstein would write in 1918.

But there was something uncanny about Besso. Over the coming years, he would always show up at exactly the right moment, the perfect *deus ex machina*, handing Einstein books, innocently offering suggestions, prodding him, goading him, nudging him onto the right path, as if he had a plan. "I … watch my friend Einstein struggle with the great Unknown," he would write, "the work and torment of a giant, of which I am the witness—a pygmy witness—but a pygmy witness endowed with clairvoyance."

That Saturday night, though, all of that lay in the future. For now, they became fast friends—best friends, really. They talked for hours on end. For his first act of camaraderie, Besso handed Einstein two books, insisting that he read them. They were the works of Ernst Mach, the final actor in this three-man play.

Perhaps you've heard of Ernst Mach. Mach 1, Mach 2, Mach 3, *that* Mach. His name is a unit of speed, and—despite his beard—a brand of razors. He was a physicist, a physiologist, a philosopher. A little bit of everything, really. You could find the young Mach in the Austrian countryside carefully observing nature—staring at a leaf or a shadow or a cloud with the utmost concentration and scrutiny, then scrutinizing his scrutinizing, noting his every sensory glitch and glimmer, building a taxonomy of tricks that our eyes can play. He collected bugs and butterflies. He tested the reactions of various materials—in trying to see whether camphor would ignite, he burned off his eyelashes and eyebrows. But it was when he was 15 years old that a single moment changed everything.

"On a bright summer day in the open air, the world with my ego suddenly appeared to me as *one* coherent mass of sensations," he later wrote. He felt, in that moment, there was no reality sitting "out there," independent of his sensations, and likewise that there was no self sitting "in here," independent of its sensations. He grew certain that there could be no real difference between mind and matter, between perceiving subject and perceived object. "This moment was decisive for my whole view," he wrote.

From that day forward, he vehemently rejected any form of dualism: the idea that the external world was made up of substantial material objects—*things*—while the mind was made of something else, so that the world we experience in consciousness is a mere copy of an actual world that lies forever hidden from us. Instead he grew convinced that mind and matter were made of the same basic ingredient. It couldn't be a physical ingredient, he argued, because how would bare matter ever give rise to subjective experience? But it couldn't be a mental ingredient either, he said, because he was certain that the self was equally an illusion. The only way to unite mind and matter, he decided, was to presume that they were made not of objective atoms, and not of subjective qualia, but of some neutral thing, an "element," he called it, which in one configuration would behave as material substance and in another as immaterial mentation, though in itself it would be neither and nothing.

"There is no rift between the psychical and the physical, no inside and outside, no "sensation" to which an external "thing," different from sensation, corresponds," he wrote.

"There is but one kind of elements, out of which this supposed inside and outside are formed—elements which are themselves inside or outside, according to the aspect in which, for the time being, they are viewed." These elements "form the real, immediate, and ultimate foundation."

Mach's view—neutral monism, it would later be called—required that every single aspect of reality, from physical objects to subjective sensations, be purely relational, so that whether something was "mind" or "matter" was determined solely by its relations with other elements and not by anything inherent to itself. It was a radical idea, but it seemed plausible. After all, Mach said, science is based on measurement, but "the concept of measurement is a concept of relation." What we call length or weight, for instance, is really the relation between an object and a ruler, or an object and a scale.

It dawned on Mach, then, that if we could rewrite science solely in terms of what can measured, then the world could be rendered entirely relational—entirely *relative*—and the mind and universe could be unified at last. But that was going to require a new kind of physics.

By 1904, *Don Quixote* had become one of Einstein's favorite books.

Two years earlier, an unemployed Einstein had put an ad in the newspaper offering physics tutoring for three francs an hour, and a philosophy student named Maurice Solovine had shown up at his door. They started talking about physics and philosophy and didn't stop; the whole tutoring thing never even came up. Soon Conrad Habicht, a mathematics student, joined the conversation, and the three young bohemians formed something of a book club for highbrowed degenerates. They read works of philosophy and literature and discussed them, sometimes until one in the morning, smoking, eating cheap food, getting rowdy and waking the neighbors. They met several nights a week. In mockery of stuffy academia, they dubbed themselves the Olympia Academy.

Besso was in Trieste working as an engineering consultant, but he came when he could, and as Einstein's closest friend, he was made an honorary member of the Academy. Under Besso's influence, the Olympians read and discussed Mach. Eventually Einstein landed a job at the Patent Office in Bern, and in 1904 he got Besso a job in the same office, so they could work side by side. In the evenings, the Academy read *Don Quixote*. It struck a chord with Einstein—later, when his sister Maja lay dying, he would read it to her. As for the Olympia boys, who can say whether they noticed it then: how Besso had become the Sancho Panza to Einstein's Quixote. When Solovine and Habicht left, it was just Einstein and Besso, walking home together from the patent office, discussing the nature of space and time and, as always, Mach.

Mach's plan to unite matter and mind required that every last bit of world be rendered relative, with nothing left over. But there was one stubborn obstacle standing in the way: According to physics, all motion was defined relative to absolute space, but absolute space wasn't defined relative to anything. It just existed, self-defined, like the basement level of reality—it wouldn't budge. Mach knew of this obstacle, and it rankled. He criticized Newton's "conceptual monstrosity of absolute space"—the idea of space as a thing unto itself. But how to get around it?

For years it had been bugging Einstein that all attempts on an observer's part to determine whether or not he was at rest relative to absolute space were doomed to fail. For every experiment he could think of, nature seemed to have a clever trick up its sleeve to hide any evidence of absolute motion. It was so downright conspiratorial that one might suspect, as Einstein did, that absolute space simply didn't exist.

Following Mach's lead, Einstein wanted to assert that motion was not defined by reference to absolute space, but only relative to other motion. Unfortunately, the laws of physics seemed to suggest otherwise. The laws of electromagnetism, in particular, insisted that light had to travel at 186,000 miles per second regardless of the observer's frame of reference. But if all motion was relative, the light's motion would have to be relative too—traveling 186,000 miles per second in one reference frame and some other speed in another, in blatant violation of electromagnetic law.

So Einstein went to see Besso. "Today I come here to battle against that problem with you," he announced when he arrived.

They discussed the situation from every angle. Einstein was ready to give up, but they hammered away.

The next day, Einstein returned. “Thank you,” he said. “I’ve completely solved the problem.” Within five weeks, his theory of special relativity was complete.

What magic words had Besso uttered in that fateful conversation? It seems he reminded Einstein of Mach’s central idea: *a measurement is always a relation.*

Einstein and Besso discussed this—what two quantities we compare in order to measure time. “All our judgments in which time plays a part are always judgments of *simultaneous events*,” Einstein realized. “If, for instance, I say, ‘That train arrives here at 7 o’clock,’ I mean something like this: ‘The pointing of the small hand of my watch to 7 and the arrival of the train are simultaneous events.”

But how does one know that two events are simultaneous? Perhaps you’re standing still and you see two distant lights flash at precisely the same moment. They’re simultaneous. But what if you had been moving? If you happened to be moving in the direction of flash A and away from flash B, you’d see A happen first, because B’s light would take ever so slightly longer to reach you.

Simultaneity is not absolute. There’s no single “now” in which all observers live. Time is relative. Space, too.

It all dawned on Einstein then: It *was* possible for all observers to see light moving at exactly 186,000 miles per second regardless of their own state of motion. The light’s speed is a measure of how much distance it covers in a given amount of time. But time changes depending on your state of motion. So even if you’re moving relative to the light, time itself will slow down precisely long enough for you to measure light’s speed at the very one required by Maxwell’s equations.

Einstein’s 1905 paper “On the Electrodynamics of Moving Bodies” introduced the world to the theory of relativity, in which time and space can slow and stretch to account for an observer's relative motions. It included no references whatsoever, but it ended with this final paragraph: "In conclusion I wish to say that in working at the problem here dealt with I have had the loyal assistance of my friend and colleague M. Besso, and that I am indebted to him for several valuable suggestions."

Einstein proudly sent his work to Mach, and seemed almost giddy when Mach responded with his approval. "Your friendly letter gave me enormous pleasure," Einstein replied. "I am very glad that you are pleased with the relativity theory … Thanking you again for your friendly letter, I remain, your student, A. Einstein."

Einstein had a long way to go, however, to see Mach's vision through. The problem was that special relativity only relativized motion for observers moving at a constant speed. The question of accelerated observers—those who were changing speed or rotating—was far trickier. Within special relativity, there was no way to blame the force that comes with acceleration on relative motion. Absolute space lingered.

In 1907, Einstein made a breakthrough. It was the happiest thought of his life, he would later say: In small regions of space, an observer would be unable to tell whether he was accelerating or at rest in a gravitational field. This suggested that it might be possible to do away with the absolute nature of acceleration—and with it absolute space—once and for all. Gravity, it seemed, was the secret ingredient that made *all* motion relative, just as Mach had wanted. And that gave a whole new meaning to the very nature of gravity: The path of an accelerated observer through spacetime traces a curve, so if acceleration was equivalent to gravity, then gravity was the curvature of spacetime. It would be some time before Einstein brought his general theory of relativity to fruition, but for now, he knew he was on the right track.

Excited, Einstein wrote a letter to Mach informing him of his progress and the publication of his newest paper. A new theory of gravity was underway, he said, and as soon as he could prove it correct, "your inspired investigations into the foundations of mechanics … will receive a splendid confirmation." In other words: *I've done what you wanted*. He published his theory of general relativity in 1915; the next year, Mach died.

Einstein wrote a long and moving obituary, glowing with praise for Mach's scientific vision, with its central point, as Einstein wrote, that "physics and psychology are to be distinguished from each other not by the objects they study but only by the manner of ordering and relating them." He argued that Mach himself was close to coming up with the theory of relativity, and wrote, with palpable admiration and innocence, that Mach "helped me a lot, both directly and indirectly."

That, however, was the apogee of the kinship between Einstein and Mach's philosophy. Einstein would eventually disavow the pure relativism of his mentor, and even to split from his Sancho. The rift begins with a most unlikely event: words from beyond the grave.

In 1921, Mach's book *The Principles of Physical Optics* was published posthumously, and contained a preface written by the author around 1913, shortly after Einstein had sent him the early paper on general relativity.

"I am compelled in what may be my last opportunity, to cancel my views of the relativity theory," Mach wrote. "I gather from the publications which have reached me, and especially from my correspondence, that I am gradually becoming regarded as the forerunner of relativity … I must as assuredly disclaim to be a forerunner of the relativists …"

Mach had likely seen what Einstein would only later come to terms with—that the so-called general theory of relativity did not live up to its name. General relativity was an unprecedented intellectual feat—but it didn't make everything relative, as Mach had dreamed. In the final version of the theory, the equivalence between acceleration and gravitation, which had seemed to make all motion relative, turned out to hold only for infinitesimally small regions of space. Patching together local regions into one big universe produced misalignments at their edges, like flat tiles on a round globe. The misalignments revealed the curvature of spacetime—a global geometry that couldn't be transformed away by a mere change in perspective. Each local region—a self-consistent, relative world—turned out to be the tiny tip of an enormous, four-dimensional iceberg, forever hidden from sight and decidedly *not* relative.

It must have been an unsettling feeling for Einstein—watching his theory gather steam and speed away from him, proving the very thing he had set out to disprove. The problem was that, according to the theory, spacetime geometry was not fully determined by the distribution of matter in the universe, so that even if you removed everything observable, some extra ingredient still remained—spacetime itself, dynamic yet absolute. It created an unbridgeable divide between the physical world and the mind, inviting, in its realist stance, a whiff of pure belief, even mysticism—the belief in a four-dimensional substratum, the paper on which reality is drawn, though the paper itself is invisible.

Einstein continued to push Mach's view for several years after publishing general relativity in 1915, living in total denial of the fact that his own theory went against it. He tried everything under the sun to mold his theory into the shape of Mach's philosophy—making the universe finite but unbounded, adding a cosmological constant—but it just wouldn't fit. "The necessity to uphold [Mach's principle] is by no means shared by all colleagues," he said, "but I myself feel it is absolutely necessary to satisfy it."

So when Einstein first read Mach's preface, it must have stung. We can hear his hurt in a comment he made at a lecture in Paris in 1922, shortly after Mach's preface was published. Mach was "*un bon mecanicie*n," Einstein said bitterly, but a "*deplorable philosophe*." He would no longer claim that his theory was one of Machian relativism, and by 1931 he would abandon Mach's views completely. "The belief in an external world independent of the perceiving subject is the basis of all natural science," he wrote. When asked how he could believe in anything beyond our sensory experience, he replied: "I cannot prove my conception is right, but that is my religion." And in 1954, a year before his death: "We ought not to speak about the Machian Principle anymore."
What Mach had never known—couldn't have known—was that his true devotee had never been Einstein. It was Besso.

Besso, that pygmy witness endowed with clairvoyance, saw exactly where Einstein's departure from Mach would soon lead him astray: in the realm of quantum mechanics.

As Einstein came to grips with Mach's rejection of relativity, the world of physics was rocked by quantum theory, a revolution Einstein had helped to spark but now refused to join. While he was making peace with an absolute spacetime—an absolute *reality*—quantum mechanics was rendering the world even more relative. The theory suggested that the outcomes of measurements could be defined only in relation to a given experiment: An electron might be a wave relative to one measuring apparatus and a particle relative to another, though in itself it was neither and nothing. In the words of Niels Bohr, the purpose of the theory was "to track down, so far as it is possible, relations between the manifold aspects of our experience"—relations and nothing more. In other words, quantum theory picked up Mach's program right where Einstein left off, a point that both Bohr and Besso were quick to emphasize.

When Einstein, complaining about a colleague's work, joked to Besso that, "He rides Mach's poor horse to exhaustion," Besso replied, "As to Mach's little horse, we should not insult it; did it not make possible the infernal journey through the relativities? And who knows—in the case of the nasty quanta, it may also carry Don Quixote de la Einsta through it all!"

"I do not inveigh against Mach's little horse," Einstein responded, "but you know what I think about it. It cannot give birth to anything living."

The truth was, Einstein's belief in a hidden reality had lain dormant for years, ever since he was a little boy—4, maybe 5—and his father had come to his bedside and handed him a compass. Einstein had held it in his hand, and found himself trembling in awe. The way the needle quivered, tugged northward by some invisible force, overwhelmed him with the feeling that "something deeply hidden had to be behind things." Now he glimpsed it again in the mathematics of general relativity. With Mach's approval moot, the awe he'd felt as a boy returned to him. When Besso tried to steer him away—toward Mach, toward the quantum— Einstein reproached his faithful squire: "It appears that you do not take the four-dimensionality of reality seriously."

The reinvention of Einstein as a young iconoclast who embraced Mach's view and ran with it, determined to create a theory of pure relativity despite his natural realist leanings—was it actually Besso's doing? Had the squire steered his master? In the short story "The Truth About Sancho Panza," Franz Kafka suggests that this reversal is, in fact, the key to Cervantes' tale. Don Quixote, he wrote, was Sancho Panza's own creation, an alter ego invented to carry out some inner vision Panza himself was ill equipped to face. "I owe to you the scientific synthesis that without such a friendship one would never have acquired—at least, not without expending all one's personal forces," Besso wrote to Einstein—as if to say, *thanks for working out that theory for me*. But the synthesis was incomplete. Having guided Einstein to water, Besso appears to have failed to make him drink.

Besso never gave up on luring Einstein back to Machian relativity. But *Don Quixote* had abandoned the knighthood for good, leaving Sancho to fend off the windmills for himself. In Princeton, New Jersey, his hair now white and wild, Einstein sat at a cluttered desk and struggled with reality while physics marched on without him. In Geneva, Switzerland, in the University mathematics library, his wiry beard now blanched with time, Besso sat hunched over his own pile of books, and worked—quietly, mysteriously—alone.

Amanda Gefter is a physics writer and author of Trespassing on Einstein's Lawn: A father, a daughter, the meaning of nothing and the beginning of everything. *She lives in Cambridge, Massachusetts.*

To Fix the Climate, Tell Better Stories

The missing climate change narrative.

BY MICHAEL SEGAL APRIL 13, 2017

Peter Sheridan Dodds has a nickname for us humans: *Homo narrativus*. Dodds, a professor at the University of Vermont, uses mathematics to study social networks. He has argued that people see the stories of heroes and villains, where there are really just networks and graphs. It's our desire for narrative, he says, that makes us believe that something like fame is the result of merit or destiny and not a network model quirk.

That we love heroes is something we can all intuitively understand. Less obvious is that **climate, too, has a considerable narrative weight and is something we understand through storytelling. "Climate cannot be experienced directly through our senses," writes Mike Hulme in his book *Why We Disagree about Climate Change*. "Unlike the wind which we feel on our face or a raindrop that wets our hair, climate is a constructed idea that takes these sensory encounters and builds them into something more abstract."** That abstraction has a moral and a historical quality: from the portrayal of flood myths as part of our relationship with the divine, to the birth of fictional monsters like Frankenstein in the wake of climate events, to our association of storms and earthquakes with emotional states—climate has always been more than a mathematical average of weather. In fact, **Hulme says, it is only recently, and primarily in the West, that the cultural and physical meanings of climate have become so separated.**

That separation has contributed to a narrative vacuum—and, like nature itself, people abhor a vacuum. We fill it with the narratives we have at hand, even if they are powerfully at odds with each other. This goes some way to understanding the vitriol of the climate debate. **"The ideological freightage we load onto interpretations of climate and our interactions with it," writes Hulme, "are an essential part of making sense of what is happening around us today in our climate change discourses."** Stories about the virtues and evils of capitalism, the role of divine control, nationalist values, and so on, are not so much maliciously inserted into what could be a sober conversation but are an inevitable response to a story that is incomplete without them.

Faced with an absence, we revert to old narratives, and there are few older than utopia and dystopia. The skeptic storyline of the rise of a dictatorial world government usurping American values must be considered not as a unique reply to climate change but as the latest instance of a well-established dystopic trope, stoked by the climate narrative vacuum. Something similar can be said for attacks on the capitalist enterprise from the left. The public, for its part, is served visions of an apocalyptic future, whether it's from politicians or from Hollywood—and, simultaneously, the utopianism of far-distant science fiction, which as a category is consumed in greater quantity than science journalism and which reflects and encourages what sociologists call "optimism bias" or "technosalvation." These utopian instincts are strengthened by a historical data point obvious to all: Our species has survived every obstacle we've encountered, and we are still here.

[…]

This is not to say that the climate conversation is irreparably broken. It's true we can't take away those unhelpful narratives that have already been attached to it**. But we can add new ones, and some narratives are more powerful than others. Scientific narratives, if they're done right, are some of the most powerful of all. They teach us more than facts, mechanisms, and procedures. They convey a worldview of skeptical empiricism and indefinite revision, show us how to negotiate the boundary between our rational and emotional selves, teach us to suspend judgment and consider all the possibilities, and remind us that a belief in objective truth is a deep kind of optimism with massive dividends. Perhaps most important of all, they situate us in the world.**

The successful assimilation of broad narratives from astronomy and genetics reminds us how powerful science narrative can be. We think of ourselves today as genetic machines, carrying around an adaptive program, which we inherit and pass on, doing so on this one habitable planet among countless others in a universe with a finite age. These facts have become intuitions and a part of our identity. The goal of climate change coverage should be a similar creation of intuition from fact. Intuition that our planet is a dynamic thing, that its environment is highly interconnected, that it has been remade many times by things living and dead.

Are we getting that done? The media has communicated the basic facts behind climate change well enough: the famous line graph of rising carbon dioxide levels, the 300 parts per million line in the sand, the northward migration of adapting species, and the endangerment of those left behind. But the narrative around these facts is more obscure. **In the words of social scientists Susanne Moser and Lisa Dilling, science communicators "often assume that a lack of information and understanding explains the lack of public concern and engagement, and that therefore more information and explanation is needed to move people to action."[3] Many of these facts are, by now, either uncontested or unsurprising. It is the narratives around them that are missing.**

Kirk Johnson, director of the Smithsonian National Museum of Natural History, puts it this way: "If you look at how the media treats scientific discoveries, they'll go to the wonder. ... [They'll say] 'here's this thing that's been discovered,' not the process of how we figured it out. And I think that understanding of how we know what we know is so critical ... If you don't help people understand what those processes are, [if] you just say 'here's the answer,' now they can go onto the web and dial up an alternate answer. I think we're seeing an erosion of credibility of science to the public because of this <u>huge flood of technology and information</u>."

[…]

Even scientists need to lure each other with narratives. The philosopher Rom Harré offers up that pillar of modern professional science, the scientific paper, as exhibit A. He argues that the three-part structure of the typical paper (hypothesis, results, and inductive support) is a post facto interpretation: "Anyone who has ever done any actual scientific research knows that this is a tale, a piece of fiction. The real-life unfolding of a piece of scientific research bears little resemblance to this bit of theatre."[1] Speaking as both a former scientist and a former

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[1] 7. Harré, R. Some narrative conventions of scientific discourse. In Nash, C. (Ed.) *Narrative in Culture: The Uses of Storytelling in the Sciences, Philosophy, and Literature* New York: Routledge, New York, NY (1990).

academic editor, I can attest to the truth of this statement. From the lab to the publisher's desk, **narrative is constantly helping to organize, sell, and drive science. As Harré puts it, "Science must present a smiling face both to itself and to the world." If narrative is necessary for one scientist to convince another of his or her result, it's certainly necessary to engage and convince the public.**

The narrative questions around climate change are broad. What does it mean for there to be a scientific consensus? How is the scientific method properly applied to a system that resists experimentation? What does a complex system look like? What is the nature of risk and probability? Each has a direct bearing on the climate change conversation without necessarily being about climate change. **They, and others like them, constitute a suprascientific narrative that is necessary for science to become culture. In a way, every good science story is a story about all of science and helps us understand every other science story.**

So let's tell more of them.

EXCERPT: HOPE JAHREN'S TRIBUTE TO HELEN KELLER IN NAUTILUS MAGAZINE

Born in Tuscumbia, Alabama, in 1880, Helen Keller thrived as a healthy infant for 19 months, until she fell ill with what was probably meningitis. She survived the raging fever but permanently lost both her sight and her hearing. […]

Keller describes the outcome of her illness as having "plunged me into the unconsciousness of a new-born baby," and then recounts how this new state became normal: "I got used to the silence and darkness that surrounded me and forgot that it had ever been different." The next two chapters describe the five-and-a-half years that Keller struggled to understand the world she was living in and communicate with those around her, without the benefit of a common language.

Most people are familiar with the moment when Anne Sullivan helped the 7-year-old Keller make a tactile connection between the concept of running water and the motion of hands spelling out its English name, "W-A-T-E-R." Keller herself described that moment as "my soul's sudden awakening." But Keller's writing makes it clear that her soul—as well as intellect—was actually wide awake well before that particular epiphany. […]

Throughout these early chapters, Keller gushes over the violets, lilies, roses, honeysuckles, Southern smilax, trailing clematis, "drooping jessamine," and other flowers that were planted throughout her family's cottage property. In the complete absence of sight and sound, Keller navigated the world for years using exclusively smell, touch, and taste. We can almost smell and touch *with* her when Keller remembers the roses of her childhood home:

They used to hang in long festoons from our porch, filling the whole air with their fragrance, untainted by any earthy smell; and in the early morning, washed in the dew, they felt so soft, so pure …

Keller relied upon her intimate familiarity with the flowers and plants near the house in order find her way around; for example, the feel of the "square stiff boxwood hedges" that marked the edge of the property. She differentiated each tree and fencepost by the pattern of the

EXCERPT: HOPE JAHREN'S TRIBUTE TO HELEN KELLER IN NAUTILUS MAGAZINE

English ivy wrapped upon it. That fateful well-house where she first learned to sign? Keller remembers getting there by walking toward the "fragrance of the honeysuckle with which it was covered."

"My hands felt every object and observed every motion, and in this way I learned to know many things," explains Keller, going on to describe how she recognized each article of clothing by slight differences in the feel of the fabric, and thus helped to sort the laundry. Keller sensed the air moving when the front door opened, and the floor vibrating when it was trod upon, and so learned to anticipate the comings and goings of the people that she knew.

The simple joys of childhood were not lost on Keller: She loved to pet the cows while they were being milked, grind spices, pick through raisins, and lick stirring spoons. Each time I read Keller's work, I am reminded that I should use *all* of my senses as I study the world, that I should periodically scour the corners of my imagination for hints that my subconscious may be dropping, fueled as it is by information that I cannot recognize as having consciously acquired. […]

The climax of Keller's childhood occurred during the summer of 1887 when Anne Sullivan convinced her that "everything had a name, and each name gave birth to a new thought." Her joy in finding that she was not alone in her need to label and categorize the world's objects was unbridled, even in its telling more than a decade later:

As we returned to the house, every object which I touched seemed to quiver with life. That was because I saw everything with the strange, new sight that had come to me.

This beautiful description of how taxonomy can awaken us to our surroundings has long been my favorite answer as to why I still require students to memorize the anatomy of the flower, the epochs of the Cenozoic, the reactions of the Krebs cycle. "As my knowledge of things grew, I felt more and more the delight of the world I was in," wrote Keller. As a teacher, I am fortunate to see this play out—to see this same flower open—year after year in my classroom.

http://nautil.us/blog/my-personal-hero-hope-jahren-on-helen-keller

Crash Course

Can a seventeen-mile-long collider unlock the universe?

Elizabeth Kolbert   May 14, 2007 Issue

Part of the Compact Muon Solenoid particle detector is lowered into place several hundred feet below ground.COURTESY CERN

The European Organization for Nuclear Research, known as CERN, has its offices on the outskirts of Geneva, in an area once devoted to dairy farms and now given over to sprawl. The offices occupy several dozen buildings, some of them in Switzerland and the remainder, a few hundred yards away, in France. The buildings are reachable by roads with names like Route Bohr, Route Schrödinger, and Route Curie. By the entrance to the complex, there is a museum—nearly empty the day I visited—that attempts to make particle physics comprehensible to the general public. Behind that there is a park where bits of old cyclotrons are displayed, like playground equipment from Mars.

If you think of the sciences as a tower, with one field resting on another until you reach, say, botany or physiology, then particle physics represents the bottommost floor. The first key experiment was conducted in 1909, under the direction of Ernest Rutherford. When Rutherford shot alpha particles at a wafer-thin sheet of gold foil, a small proportion of the particles bounced right back, a phenomenon that he described as "almost as incredible as if you fired a fifteen-inch shell at a piece of tissue paper and it came back to hit you." Rutherford's work led to the realization that most of an atom's mass was concentrated in a tiny area, the nucleus. "All science is either physics or stamp-collecting," he is supposed to have said.

Since Rutherford's discovery, particle physics has provided one extraordinary—if increasingly implausible-sounding—revelation after another: first protons and neutrons, then antimatter, gluons, neutrinos, and quarks. In 1967, the existence of particles to mediate the weak force, which is responsible for radioactive decay, was theorized; in 1983, at CERN, these particles—the W and the Z—were observed and their properties measured. In 1977, the existence of what became known as the "top" quark was predicted; in 1995, at Fermilab, in Illinois, it, too, was found.

And yet, for all its triumphs, the field has been haunted by failure. The more physicists have learned about the way matter behaves at its most fundamental level, the more acutely they have become aware that something—a big something—is missing from their accounts. Among the many possibilities proposed for what's often called "new physics" is that the universe actually consists of tiny strands (or strings) of energy; that it contains several dimensions beyond those that we perceive; that it is full of mysterious particles—"sparticles"—that have yet to be detected; that it is not a universe at all but a multiverse; and that it began not with a bang but with a splat.

Sometime in the next few months, physicists at CERN will finish preparations for the most ambitious particle-physics experiment ever, which will be conducted in an apparatus modestly referred to as the Large Hadron Collider, or L.H.C. The L.H.C. fills a circular tunnel seventeen miles in circumference. To get from one side of it to the other, it is necessary to drive through several towns, and then descend three hundred feet in an elevator. Alternatively, it is possible to ride through the tunnel in one of the dozens of bicycles CERN provides for its staff, but in that case a supply of emergency oxygen is required.

The L.H.C. is considered the best—some would say the only—hope for testing the theories of "new physics" against material reality. Once the collider begins operating at full power—in early 2008, if all goes well—nearly half the particle physicists in the world will be involved in analyzing its four-millionmegabyte-per-hour stream of data. Few events in the history of science have had a bigger buildup. It's been suggested that the L.H.C. will unlock the secrets of the universe or, barring that, prove this ambition to be hopeless.

The L.H.C. is a kind of Babel built underground. Dozens of countries have manufactured its components, and dozens more have lent manpower and expertise. (Some contracts went to Russian physicists who previously worked for the Soviet military; in this way, the collider has provided a livelihood for scientists whose employment options might otherwise include selling nuclear secrets.) When I ate in CERN's lunchroom, I heard people speaking English, French, German, and Italian, as well as several languages that I couldn't identify. The place was so crowded that it took me five minutes to pay for a cup of coffee, proving the elemental truth that man can build a superconducting collider but not a functional cafeteria.

CERN's chief scientific officer, Jos Engelen, is from the Netherlands. He serves under the director general, who is from France, and alongside the chief financial officer, who is from Germany. I went to speak to Engelen in his office; behind his desk a chart indicated when the various parts of the collider are supposed to be completed. It was a crazy quilt of multicolored blocks, with lines radiating in all directions. Engelen greeted me with a half-ironic cheerfulness that struck me as very Dutch. Among his responsibilities is dealing with the frequent calls and letters CERN receives about the possibility that the Large Hadron Collider will destroy the world. When I asked about this, Engelen picked up a Bic pen and placed it in front of me.

"In quantum mechanics, there is a probability that this pen will fall through the table," he said. "All of a sudden, it will be on the floor. Because it can behave as a wave, it can go through; we call that the 'tunnel effect.' If you calculate the probability that this happens, it is not identical to zero. It is a very small probability. But it never happens. I've never seen it happen. You have never seen it happen. But to the general public you make a casual remark, 'It is not identical to zero, it is very small,' and . . . " He shrugged.

Worries about the end of the planet have shadowed nearly every high-energy experiment. Such concerns were given a boost by *Scientific American*—presumably inadvertently—in 1999. That summer, the magazine ran a letter to the editor about Brookhaven's Relativistic Heavy Ion Collider, then nearing completion. The letter suggested that the Brookhaven collider might produce a "mini black hole" that would be drawn toward the center of the earth, thus "devouring the entire planet within minutes." Frank Wilczek, a physicist who would later win a Nobel Prize, wrote a response for the magazine. Wilczek dismissed the idea of mini black holes devouring the earth, but went on to raise a new possibility: the collider could produce strangelets, a form of matter that some think might exist at the center of neutron stars. In that case, he observed, "one might be concerned about an 'ice-9'-type transition," wherein all surrounding matter could be converted into strangelets and the world as we know it would vanish. Wilczek labelled his own suggestion "not plausible," but the damage had been done. "BIG BANG MACHINE COULD DESTROY EARTH" ran the headline in the London *Times*. Brookhaven was forced to appoint a committee to look into this and other disaster scenarios. (The committee concluded that "we are safe from a strangelet initiated catastrophe.")

"I know Frank Wilczek," Engelen told me. "He is an order of magnitude smarter than I am. But he was perhaps a bit naïve." Engelen said that CERN officials are now instructed, with respect to the L.H.C.'s world-destroying potential, "not to say that the probability is very small but that the probability is *zero*."

I asked Engelen how he would explain the project of particle physics to a non-physicist, or if he thought such an explanation was even advisable. "We simply want to know what the world is made of, and how," he said. "What is in here"—he rapped on his desk with his knuckles—"and how these particles in here constitute a table."

"Let us start with Ernest Rutherford in the beginning of the last century," he went on. “Rutherford understood what an atom looks like. It is a fat, heavy nucleus, with very light electrons orbiting around. The next step is we discovered objects inside the nucleus, one called the proton, the other the neutron. That is the pattern. As a next step, people started to wonder about these protons and neutrons, whether there is structure in there. And they started probing that. And they found that there is structure in there. There are quarks in there. And what we want is to reduce the world to objects that have no structure, that are points, that are as simple as we can imagine. And then build it up from there again.”

So far, physicists have succeeded in observing sixteen pointlike, or fundamental, particles, a number that increases if you count antimatter particles, or if you differentiate among, say, the eight types of gluons. Particles in the largest group, called fermions, in honor of Enrico Fermi, are the stuff of matter. Fermions include electrons and quarks, which come in the whimsical-sounding varieties up, down, charm, strange, top, and bottom. (A hadron is a collection of quarks, or quarks and antiquarks. A proton is a hadron composed of two up quarks and one down; a neutron consists of two downs and one up.) Fermions also include neutrinos, which, somewhat unnervingly, stream through our bodies at the rate of trillions per second. “Neutrinos, they are very small,” John Updike’s poem “Cosmic Gall” observes. “And do not interact at all.”

Hypothetically at least, there is also a seventeenth particle, known as the Higgs. The Higgs particle was first postulated more than forty years ago by the Scottish physicist Peter Higgs, and has been sought—fruitlessly—at every major collider built since then. Its discovery would have many fantastic implications, one of which is that the void of space is not really void but is permeated by an invisible field that acts a bit like cosmic molasses. This Higgs field, if it exists, exerts a drag on matter passing through it, lending mass to particles that otherwise wouldn’t have any. Without the Higgs, physicists have no way to explain why fundamental particles weigh anything at all, since, according to theory, they should be massless. The fact that the Higgs is central to modern physics even though it has never been found has prompted one Nobel laureate to label it the rug under which the discipline sweeps its ignorance and a second to dismiss it as the “toilet” into which physics flushes its inconsistencies. A third Nobel winner has labelled it the “God particle.”

“We are going to make that particle,” Engelen told me. “Or we are going to show that it doesn’t exist.”

The day that I met with Engelen, I also spoke with the deputy head of CERN’s physics department, Michael Doser. Doser is tall and lanky, with fuzzy blondish hair and a narrow stripe of beard that runs down the middle of his chin. His primary interest is antimatter.

“If you think about what matter is, you end up with a very Zen-like answer,” he told me. “If you look at what a quark is, or an electron, the primary constituents of matter, they’re pointlike particles. They have no spatial extent. They have a number of properties, like mass and charge, and that’s it. In a way, they’re mathematical figments, and they’re separated by vacuum—mathematical figments in nothing. And antimatter is the opposite—mathematical figments with the opposite charge.” When matter and antimatter meet, they annihilate each other in a burst of energy. It is believed that in the Big Bang equal quantities of matter and antimatter were produced. But this theory makes it difficult to explain certain basic facts, like you and me and countless galaxies. How to account for the abundance of matter in the universe, and the shortage of antimatter, Doser told me, “is one of the most embarrassing questions in particle physics.”

Doser began his career at CERN in 1991, at which point most of the physicists at the organization were working on a project known as the Large Electron-Positron Collider, or LEP. Basically, LEP was a high-precision matter/antimatter demolition-derby track. Billions of electrons looping around in one direction were, at discrete intervals, made to cross paths with billions of antielectrons—or positrons—moving the opposite way. Where the beams crossed, huge detectors were set up to record the smashups.

The L.H.C., Doser explained, relies on much the same design, and, in fact, makes use of the tunnel originally dug for LEP. Instead of electrons and positrons, however, the L.H.C. will send two beams of protons circling in opposite directions. Protons are a good deal more massive than electrons—roughly eighteen hundred times more—which means they can carry more energy. For this reason, they are also much harder to manage.

“Basically, what you must have to accelerate any charged particles is a very strong electric field,” Doser said. “And the longer you apply it the more energy you can give them. In principle, what you’d want is an infinitely long linear structure, in which particles just keep getting pushed faster and faster. Now, because you can’t build an infinitely long accelerator, you build a circular accelerator.” Every time a proton makes a circuit around the L.H.C. tunnel, it will receive electromagnetic nudges to make it go faster until, eventually, it is travelling at 99.9999991 per cent of the speed of light. “It gets to a hair below the speed of light very rapidly, and the rest of the time is just trying to sliver down this hair.” At this pace, a proton completes eleven thousand two hundred and forty-five circuits in a single second.

“The more energetic the particles are, the more force you need to keep them on orbit,” Doser went on. “They want to go straight. And so you need very strong magnetic fields.” In the L.H.C., such strong fields are required that they cannot be produced by conventional, or so-called “warm,” magnets. Instead, the L.H.C. beam pipe has been encased in superconducting magnets, cooled with superfluid helium. These magnets are supposed to operate at minus 271.25 degrees Celsius—minus 456.25 degrees Fahrenheit—a temperature colder than that of deep space. Doser noted that there are many hazards involved in working with such powerful magnets; for example, if a bolt or a screw is left lying around when they are turned on, it can fly through the apparatus like a bullet. He recalled that as a graduate student he had once lost a wrench in a machine this way: “It cost me a year.” Meanwhile, if any of the magnets fail, the beams, each of which is supposed to contain something like three hundred trillion protons, could veer off course and, in short order, burn a hole through the collider. “That’s why people are so nervous about starting up,” Doser said. (In fact, a few weeks after my visit to CERN, during a test of a set of magnets known as an “inner triplet,” a support failed, bursting a pipe and spewing helium into the tunnel. The failure of the support, which was produced in the United States, was attributed to a simple engineering error.)

When protons crash into each other at 99.9999991 per cent the speed of light, the resultant mess is usually just that—the subatomic equivalent of shattered glass and twisted metal. But stranger things can happen. Just as it is possible to convert mass into energy—as in a nuclear explosion—the reverse is also true: energy can be transformed into mass according to the Einsteinian equation $E=mc2$ (c being the speed of light). In this way, new particles can be produced that are more massive than those that entered the collision in the first place. The process might be compared to smashing two high-speed Priuses into each other and finding that they have rematerialized as a tank.

By now, the Higgs has been sought for so long that physicists have a pretty clear idea of how much it must weigh. The lower bound is around 120 times more than a proton—or roughly 2×10^{-22} grams. The upper bound is about 210 times as much as a proton. The most powerful collider currently in operation is Fermilab’s Tevatron, outside Chicago. The Tevatron, which smashes protons into antiprotons, can accelerate particles to an energy of just under a trillion electron volts, or one TeV. (An electron volt is the amount of energy acquired by a single electron falling through a potential difference of one volt.) So far, the Tevatron has failed to reveal the Higgs, though physicists there are actively looking for it. The L.H.C. will accelerate particles to seven TeV, which means that it will be seven times as powerful as the Tevatron. This should be more than enough energy to produce the Higgs, if there is a Higgs to produce. It may also be enough to uncover much more than the

Higgs. Depending on how the universe is constructed, extra dimensions, mini black holes, and the source of so-called “dark matter” may all be revealed at CERN. Any black holes created, Doser was quick to assure me, would be entirely benign.

On my second day at CERN, I drove out to the detector farthest from Geneva—the Compact Muon Solenoid—which is to operate in, or really underneath, the town of Cessy, France. Robert Cousins, a physicist visiting CERN from the University of California at Los Angeles, had agreed to show me around. When we met in the C.M.S. parking lot, Cousins was wearing a bright-yellow hard hat. He handed me one to put on.

The L.H.C. will have four main detectors, spaced at intervals around the tunnel like beads on a bracelet. Each is being constructed by a different team according to a different design, the theory being that any interesting phenomena missed by one should be captured by the others. The teams share information, but there is a certain amount of cheerful rivalry among them. C.M.S., in particular, has been plagued by difficulties—during excavations, the soil in Cessy proved so soupy that the ground had to be frozen with liquid nitrogen—and before I went to look at it a physicist who is not affiliated with the project told me that C.M.S. was sometimes referred to as “See a Mess.”

Cousins led me into a vast, hangarlike building where the detector was being assembled. There was a loud clanging coming from all directions. Iron rings several stories high were sitting on hydraulic lifts. At the far end of the hangar, a huge shaft dropped down several hundred feet. Cousins said that the shaft would be used to lower the detector, piece by piece, to the level of the L.H.C. tunnel. We boarded an elevator, and got out near the bottom. A section of the detector that had already been lowered into place loomed up in front of us. It looked like the underside of a rocket ship.

It is one of the paradoxes of particle physics that fundamental particles, though pointlike and indivisible, are also generally unstable. In fact, the heavier particles are so short-lived that even to speak of their having an existence seems faintly ludicrous; a top quark, for example, is estimated to last no more than 1×10^{-24} seconds. (For comparison’s sake, 1×10^{-24} centuries comes to three millionths of a billionth of a second.) When unstable particles break down, new, lighter particles are produced. Some of these are likely to be unstable as well, and to break down further. The outcome of this process is a distinctive scattering of “decay products,” which physicists refer to as a particle’s “signature.”

In order to “read” such a signature, a detector has to capture all the decay products that come flying out after a collision and measure their properties. This requires layer after layer of detecting elements; at C.M.S., these are arranged in the shape of an enormous jelly roll. The innermost layer, known as the tracker, consists of some seventy-five million silicon sensors. The next layer, which measures the energies of photons and electrons, contains eighty thousand crystals of lead tungstate. Surrounding this are brass-and-plastic scintillators for tracking hadrons and a tube-shaped magnet—a superconducting solenoid—twenty feet in diameter. Finally, there are several iron rings of increasing circumference. These hold sensors to detect muons, which are essentially heavy electrons. (Neutrinos can’t be measured directly, and are therefore factored in as an absence.) All told, the Compact Muon Solenoid will weigh twenty-eight million pounds. It will hold enough iron to reconstruct the Eiffel Tower. Apparently, “compact” is a relative term.

Cousins explained that the information gathered by each layer of C.M.S. would be analyzed virtually instantaneously, and a decision made by the detector’s computers whether to ignore the collision or to save the results for further study by recording them on tape. “There are famous high-energy-physics experiments that missed discoveries because they weren’t writing them to tape,” he told me. We were walking back through the hangar, past the giant iron rings, which were painted fire-truck red. “This is why we try not to be too specific about which theoretical speculations we care about. We add up all the energy, and if it’s a huge number we write that event to tape. If on one side of the detector it's a not-so-huge number, but there is nothing on the other side, so it's a huge imbalance, we get excited about that, and we write that to tape, too."

Only a small fraction of the protons zipping through C.M.S. at any given moment will actually crash into one another. Still, this fraction represents an enormous number. When the L.H.C. is operating at full "luminosity," it is expected that the beams will cross forty million times a second and that each crossing will produce twenty collisions. C.M.S. will write fewer than .001 per cent of the crossings to tape; even so, it will be recording six thousand per minute, or three hundred and sixty thousand per hour, or some six million per week. The three other main detectors at CERN will generate similar amounts of data. There are many ways to represent a data stream of this magnitude; one that stuck with me was in terms of CDs. If all the L.H.C. data were burned onto disks, the stack would rise at the rate of a mile a month.

Lodged somewhere in this tower of information should be the signature of the Higgs, or, really, signatures, since the particle is expected to decay in a variety of ways. These signatures will look an awful lot like the signatures of other unstable particles. One physicist I spoke to compared the computational challenge of distinguishing a Higgs to finding a needle not in one haystack but in ten. I thought it sounded more like finding a needle in a needle factory.

Particle physicists come in two distinct varieties, which, rather like matter and antimatter, are very much intertwined and, at the same time, agonistic. Experimentalists build machines. Theorists sit around and think. "I am happy to eat Chinese dinners with theorists," the Nobel Prize-winning experimentalist Samuel C. C. Ting once reportedly said. "But to spend your life doing what they tell you is a waste of time."

"If I occasionally neglect to cite a theorist, it's not because I've forgotten," Leon Lederman, another Nobel-winning experimentalist, writes in his chronicle of the search for the Higgs. "It's probably because I hate him."

A few weeks after I returned from talking to the experimentalists at CERN, I went to speak to Nima Arkani-Hamed, a theorist at Harvard. Arkani-Hamed, who is thirty-five, has an oval face, deep-set eyes, and dark, shoulder-length hair. The day I visited, he was dressed entirely in black. He immediately offered me an espresso, which he made at a little machine that spit out one cupful at a time. "I've been trying to understand something about the fact that the universe is accelerating," he explained, erasing a double-wide blackboard covered with equations.

"Often, this kind of physics is referred to as particle physics, which I don't like," Arkani-Hamed told me. "People get the mistaken impression that what we care about is the particles. The science is characterized like: What are things made of? What are the ultimate building blocks of matter? I hate that. That sounds a lot like chemistry, and it's not like that at all. There are many, many more exciting things in nature than some random elementary particles.

"The reason we go to short distances isn't to probe the building blocks of matter," he went on. "It's because for four hundred years fundamental physics has been on this trajectory of unifying seemingly disparate things. We've found that, as we understand more, apparently incredibly disparate phenomena turn out to be different aspects of a more surprising, more beautiful answer than we could have anticipated—and often even hoped for. This started with Newton, who realized that the force dragging the apple down was the same force holding the moon around the earth. It continued with the realization that electricity and magnetism are different aspects of the same thing. Relativity told us that space and time are different aspects of the same thing. There's more and more unity in our understanding of nature. And we've seen, especially over the last hundred years, that the essential unity and the essential simplicity best reveal themselves at short-distance scales. So it's not that we care about the particles. We care about the laws."

Taped to the wall of Arkani-Hamed's office is a graph labelled "LHC Luminosity Profile." It shows when various phenomena—including the Higgs

—should, if they exist, be revealed. Arkani-Hamed is a frequent visitor to CERN, and every time he goes, he told me, "it's like a religious experience." To prepare for the start-up of the collider, he has helped organize a series of dress rehearsals, called the L.H.C. Olympics. In these exercises, one team, playing God, chooses, out of the many models of the universe proposed by theorists, one to be true. The team then generates the sort of data that, according to this model, should be produced at the L.H.C. The other teams have to analyze the data to try to arrive back at the theoretical model the numbers are supposed to reflect. There are no winners or losers, Arkani-Hamed explained. "But afterward some people are high-fiving each other and other people are being consoled." He added, "It's an amazing blast."

One source of tension between experimentalists and theorists is the awkward matter of credit. Who should get the glory when a discovery is made: the theorist who proposed the idea, or the experimentalist who found the evidence for it? In this context, even access to L.H.C. data is a vexed subject; in the United States, the groups that have worked on building the detectors will receive the raw data, but they're not likely to share it. Arkani-Hamed joked that in order to get at the information theorists might have to find a "Deep Throat" who will pass them the data in secret.

"There is a sense among many experimentalists that theorists are a bunch of irresponsible little spoiled brats who get to sit around all day, having all these fun ideas, drinking espresso and goofing off, with next to no accountability," he said. "Meanwhile, they're out there, nose to the grindstone, for ten years; they've built this damn detector, and damn it if they're not going to be the ones to figure it out! And so this stuff that we're doing, there's some Johnny-come-lately feeling like 'Oh, now that it's all done the theorists finally want to think about how they're going to solve this'; it's like there are theorists swooping in to try to take it from them. I'm exaggerating slightly, but not much.

"It's a general fact about physics that the people you tend to remember are the theorists," he went on. "At least in the mythology, experiment plays a less central role. And there's a natural reason for that, because the ultimate goal isn't to observe things about nature; the ultimate goal is to understand and explain things about nature. So, for that reason, it's a chicken-and-egg problem. But definitely you want to be the chicken."

Arkani-Hamed is often called a string theorist, although he is more closely associated with ideas like large extra dimensions—large being on the scale of a tenth of a millimetre—and a hybrid theory known as "split supersymmetry." String theory posits that the universe is composed of tiny strands of energy, which vibrate at different frequencies, creating what appear to be different particles. In its most popular form, string theory demands the existence of seven dimensions beyond the usual four—three in space and one in time—that we're familiar with. Supersymmetry, meanwhile, which is often referred to by the acronym SUSY (pronounced soo-see), holds that every particle has a "superpartner" with a different spin, spin here being understood not as it is in everyday life but as a fixed property of a particle that determines some of its basic characteristics. Under the naming system that's been devised for these hypothetical superpartners, the counterpart of a quark would be a squark, and that of a photon a photino. (The superpartner of the as yet undiscovered Higgs would be a Higgsino.) It has been proposed that these "superparticles" could account for the dark matter that physicists estimate makes up nearly a quarter of the universe.

String theory and supersymmetry are enormously compelling to theorists, so much so that their proponents dominate the theory groups at most élite universities. (As of 2000, at least ten thousand scientific papers on supersymmetry, and several thousand more on string theory, had been written.) Both aim at further unification, and both—to varying degrees—resolve problems that have frustrated physicists for decades. Arkani-Hamed spent nearly two hours trying to take me through the details of just one of these—the so-called "hierarchy problem." In the process, he consumed four or five or six cups of espresso—even this I lost track of. Broadly speaking, the hierarchy problem has to do with mathematical contortions, known to physicists as "fine-tuning," that must be performed in order to account for the fact that gravity is so weak compared to the other forces.

"This is not just a little weird," Arkani-Hamed told me. "It's incredibly weird. The big question that we don't have an answer to, or that we have an answer to but it seems absurd, is: Why do we have a macroscopic universe at all?"

The trouble with string theory and supersymmetry is that, at this point, they remain entirely theoretical. The last confirmed breakthrough in particle physics was a set of equations known as the Standard Model. Developed in the early nineteen-seventies, the equations describe the behavior of all known forms of matter and all known forces, with the notable exception of gravity. Despite the model's limitations as a fundamental theory of nature—the hierarchy problem is just one of its many shortcomings—the predictions it has generated have been borne out, with astonishing precision, at one collider after another. (The Higgs would represent the last element of the model to be confirmed.) String theory, by contrast, has yet to provide a single prediction that could be definitively tested. As for supersymmetry, which is generally considered a precondition for string theory, all efforts to confirm its predictions have so far failed: at the energy levels achieved by colliders to date, not a trace of a squark or a photino has turned up. As Lee Smolin, a physicist at Canada's Perimeter Institute, observed in a recent critique of contemporary theory, eventually "you begin to feel like Sbozo the clown. Or Bozo the clownino. Or swhatever."

To theorists, the tantalizing promise of the L.H.C. is that it will, finally, supply the evidence of "new physics" that they've been waiting for. Certain patterns of missing energy, for example, would suggest the existence of extra dimensions, as would the creation of mini black holes. Different results—also in the form of missing energy—would indicate the existence of squarks or other superparticles. There are good theoretical reasons to expect these phenomena to begin to appear at the energy level of the L.H.C., or so at least

Arkani-Hamed tried to explain to me over several more espressos. He told me that he was completely confident the Higgs would be found at the collider: "I would bet many, many months' salary." He also said that if the Higgs was the only result, the L.H.C. would be a disappointment. "We theorists, we're a hard lot to please. We've taken things for granted for so long we say, 'Oh, yeah, for sure you'll discover the Higgs.' But the things we're really interested in are all these major puzzles."

Eventually, some of Arkani-Hamed's graduate students wandered into his office. They had brought with them a Diet Coke, which Arkani-Hamed began to drink out of his espresso cup, and a hundred-page paper that they—and he—were planning to release that day. The opening sentence of the paper declared, "With the upcoming turn-on of the Large Hadron Collider (LHC), high energy physics is on the verge of entering its most exciting period in a generation." (A later sentence noted, "As the reader might find intuitive, we can tremendously improve our scheme over the constant approximation by including the leading order near-threshold behavior of matrix elements.")

In 1969, the Congressional Joint Committee on Atomic Energy held a hearing at which the physicist Robert Wilson was called to testify. Wilson, who had served as the chief of experimental nuclear physics for the Manhattan Project, was at that point the head of CERN's main rival, Fermilab, and in charge of $250 million that Congress had recently allocated for the lab to build a new collider. Senator John Pastore, of Rhode Island, wanted to know the rationale behind a government expenditure of that size. Did the collider have anything to do with promoting "the security of the country"?

> WILSON: No sir, I don't believe so.
>
> PASTORE: Nothing at all?
>
> WILSON: Nothing at all.
>
> PASTORE: It has no value in that respect?

> WILSON: It only has to do with the respect with which we regard one another, the dignity of men, our love of culture. . . . It has to do with are we good painters, good sculptors, great poets? I mean all the things we really venerate in our country and are patriotic about. . . . It has nothing to do directly with defending our country except to make it worth defending.

Asked to explain how their work, supported by public funds, contributes to the public good, particle physicists often cite Wilson, or offer some variation on his non-answer answer: the search for knowledge cannot be justified on other grounds; its value, like the particles under study, is irreducible.

The cost of the L.H.C. is expected to run to more than $8 billion, and this doesn't include the price of the tunnel, which was originally dug for LEP. Most of the funding is being provided by European taxpayers; Germany has contributed the most—around twenty per cent of the total—and Britain and France have each contributed slightly less than that. (The United States is contributing a little more than $500 million.) Meanwhile, physicists are already lobbying for the next generation of machines. The plan for the International Linear Collider, which, as its name suggests, would be built in a straight line rather than a ring, calls for smashing electrons and positrons together at the midpoint of a tunnel twenty miles long. According to the Web site that has been set up for the I.L.C., the hypothetical collider's design would allow for "an upgrade" to a thirty-mile-long machine "during the second stage of the project." The even more ambitious Very Large Hadron Collider would occupy a tunnel a hundred and forty miles in circumference.

In principle, colliders could just keep on getting bigger—the Incredibly Large Hadron Collider!—and commensurately more expensive. As a practical matter, of course, there's a limit, and it's quite possible that limit has already been reached. At CERN, nearly every physicist I spoke to recalled the sad—very sad—story of the Superconducting Super Collider. Announced with much fanfare by President Ronald Reagan in 1987, the Superconducting Super Collider was supposed to occupy a tunnel fifty-four miles in circumference under Waxahachie, Texas. It was designed to generate beam energies of 20 TeV, roughly three times as high as those that will be achieved at CERN. Fourteen miles of the tunnel had been excavated—and $2 billion spent—when, in 1993, Congress pulled the plug. "If we find more basic building blocks of the universe, it's not going to change the way people live" is how Representative Martin R. Hoke, of Ohio, shrugged off his vote. As the historian of science Peter Galison pointed out to me, it is probably no coincidence that funding for the supercollider was cancelled almost immediately after the fall of the Soviet Union. The "dignity of men" defense of particle physics worked best at the height of the Cold War, when no one, except maybe the scientists involved, entirely believed it.

Unless funding for another collider materializes, a lot of experimentalists will soon find themselves out of work. "Half of those guys already have résumés in at hedge funds," one theorist joked to me. Arguably, the theorists' situation is not all that much more secure; at a certain point, speculations about the nature of the universe that can't be put to the test cease to be physics. The promise of the Large Hadron Collider is thus also its great burden. A truly astonishing discovery there—proof, say, of extra dimensions, or of something even weirder than that, which theorists have yet to conceive of—would provide a powerful impetus to keep particle physics going for another generation. Barring a breakthrough, it's hard to imagine how the project can continue. Such an outcome would not mean that the fundamental order of the universe is unknowable. But it might well mean that we will never know it. ◆

Dream Machine

The mind-expanding world of quantum computing.

Rivka Galchen May 2, 2011 Issue

On the outskirts of Oxford lives a brilliant and distressingly thin physicist named David Deutsch, who believes in multiple universes and has conceived of an as yet unbuildable computer to test their existence. His books have titles of colossal confidence ("The Fabric of Reality," "The Beginning of Infinity"). He rarely leaves his house. Many of his close colleagues haven't seen him for years, except at occasional conferences via Skype.

David Deutsch believes that quantum computers will give evidence for the existence of parallel universes.Photograph by Hans Gissinger

Deutsch, who has never held a job, is essentially the founding father of quantum computing, a field that devises distinctly powerful computers based on the branch of physics known as quantum mechanics. With one millionth of the hardware of an ordinary laptop, a quantum computer could store as many bits of information as there are particles in the universe. It could break previously unbreakable codes. It could answer questions about quantum mechanics that are currently far too complicated for a regular computer to handle. None of which is to say that anyone yet knows what we would really do with one. Ask a physicist what, practically, a quantum computer would be "good for," and he might tell the story of the nineteenth-century English scientist Michael Faraday, a seminal figure in the field of electromagnetism, who, when asked how an electromagnetic effect could be useful, answered that he didn't know but that he was sure that one day it could be taxed by the Queen.

In a stairwell of Oxford's Clarendon Physics Laboratory there is a photo poster from the late nineteen-nineties commemorating the Oxford Center for Quantum Computation. The photograph shows a well-groomed crowd of physicists gathered on the lawn. Photoshopped into a far corner, with the shadows all wrong, is the head of David Deutsch, looking like a time traveller teleported in for the day. It is tempting to interpret Deutsch's representation in the photograph as a collegial joke, because of Deutsch's belief that if a quantum computer were built it would constitute near-irrefutable evidence of what is known as the Many Worlds Interpretation of quantum mechanics, a theory that proposes pretty much what one would imagine it does. A number of respected thinkers in physics besides Deutsch support the Many Worlds Interpretation, though they are a minority, and primarily educated in England, where the intense interest in quantum computing has at times been termed the Oxford flu.

But the infection of Deutsch's thinking has mutated and gone pandemic. Other scientists, although generally indifferent to the truth or falsehood of Many Worlds as a description of the universe, are now working to build these dreamed-up quantum-computing machines. Researchers at centers in Singapore, Canada, and New Haven, in collaboration with groups such as Google and NASA, may soon build machines that will make today's computers look like pocket calculators. But Deutsch complements the indifference of his colleagues to Many Worlds with one of his own—a professional indifference to the actual building of a quantum computer.

Physics advances by accepting absurdities. Its history is one of unbelievable ideas proving to be true. Aristotle quite reasonably thought that an object in motion, left alone, would eventually come to rest; Newton discovered that this wasn't true, and from there worked out the foundation of what we now call classical mechanics. Similarly, physics surprised us with the facts that the Earth revolves around the sun, time is curved, and the universe if viewed from the outside is beige.

“Our imagination is stretched to the utmost,” the Nobel Prize-winning physicist Richard Feynman noted, “not, as in fiction, to imagine things which are not really there, but just to comprehend those things which *are* there.” Physics is strange, and the people who spend their life devoted to its study are more accustomed to its strangeness than the rest of us. But, even to physicists, quantum mechanics—the basis of a quantum computer—is almost intolerably odd.

Quantum mechanics describes the natural history of matter and energy making their way through space and time. Classical mechanics does much the same, but, while classical mechanics is very accurate when describing most of what we see (sand, baseballs, planets), its descriptions of matter at a smaller scale are simply wrong. At a fine enough resolution, all those reliable rules about balls on inclined planes start to fail.

Quantum mechanics states that particles can be in two places at once, a quality called superposition; that two particles can be related, or “entangled,” such that they can instantly coördinate their properties, regardless of their distance in space and time; and that when we look at particles we unavoidably alter them. Also, in quantum mechanics, the universe, at its most elemental level, is random, an idea that tends to upset people. Confess your confusion about quantum mechanics to a physicist and you will be told not to feel bad, because physicists find it confusing, too. If classical mechanics is George Eliot, quantum mechanics is Kafka.

All the oddness would be easier to tolerate if quantum mechanics merely described marginal bits of matter or energy. But it is the physics of everything. Even Einstein, who felt at ease with the idea of wormholes through time, was so bothered by the whole business that, in 1935, he co-authored a paper titled “Can quantum-mechanical description of physical reality be considered complete?” He pointed out some of quantum mechanics’s strange implications, and then answered his question, essentially, in the negative. Einstein found entanglement particularly troubling, denigrating it as “spooky action at a distance,” a telling phrase, which consciously echoed the seventeenth-century disparagement of gravity.

The Danish physicist Niels Bohr took issue with Einstein. He argued that, in quantum mechanics, physics had run up against the limit of what science could hope to know. What seemed like nonsense *was* nonsense, and we needed to realize that science, though wonderfully good at predicting the outcomes of individual experiments, could not tell us about reality itself, which would remain forever behind a veil. Science merely revealed what reality looked like to us.

Bohr’s stance prevailed over Einstein’s. “Of course, both sides of that dispute were wrong,” Deutsch observed, “but Bohr was trying to obfuscate, whereas Einstein was actually trying to solve the problem.” As Deutsch notes in “The Fabric of Reality,” “To say that prediction is the purpose of a scientific theory is to confuse means with ends. It is like saying that the purpose of a spaceship is to burn fuel.” After Bohr, a “shut up and calculate” philosophy took over physics for decades. To delve into quantum mechanics as if its equations told the story of reality itself was considered sadly misguided, like those earnest inquiries people mail to 221B Baker Street, addressed to Sherlock Holmes.

I met David Deutsch at his home, at four o’clock on a wintry Thursday afternoon. Deutsch grew up in the London area, took his undergraduate degree at Cambridge, stayed there for a master’s in math—which he claims he’s no good at—and went on to Oxford for a doctorate in physics. Though affiliated with the university, he is not on staff and has never taught a course. “I love to give talks,” he told me. “I just don’t like giving talks that people don’t want to hear. It’s wrong to set up the educational system that way. But that’s not why I don’t teach. I don’t teach for visceral reasons—I just dislike it. If I were a biologist, I would be a theoretical biologist, because I don’t like the idea of cutting up frogs. Not for moral reasons but because it’s disgusting. Similarly, talking to a group of people who don’t want to be there is disgusting.” Instead, Deutsch has made money from lectures, grants, prizes, and his books.

In the half-light of the winter sun, Deutsch's house looked a little shabby. The yard was full of what appeared to be English ivy, and near the entrance was something twiggy and bushlike that was either dormant or dead. A handwritten sign on the door said that deliveries should "knock hard." Deutsch answered the door. "I'm very much in a rush," he told me, before I'd even stepped inside. "In a rush about so many things." His thinness contributed to an oscillation of his apparent age between nineteen and a hundred and nineteen. (He's fifty-seven.) His eyes, behind thick glasses, appeared outsized, like those of an appealing anime character. His vestibule was cluttered with old phone books, cardboard boxes, and piles of papers. "Which isn't to say that I don't have time to talk to you," he continued. "It's just that—that's why the house is in such disarray, because I'm so rushed."

More than one of Deutsch's colleagues told me about a Japanese documentary film crew that had wanted to interview Deutsch at his house. The crew asked if they could clean up the house a bit. Deutsch didn't like the idea, so the film crew promised that after filming they would reconstruct the mess as it was before. They took extensive photographs, like investigators at a crime scene, and then cleaned up. After the interview, the crew carefully reconstructed the former "disorder." Deutsch said he could still find things, which was what he had been worried about.

Taped onto the walls of Deutsch's living room were a map of the world, a periodic table, a hand-drawn cartoon of Karl Popper, a poster of the signing of the Declaration of Independence, a taxonomy of animals, a taxonomy of the characters in "The Simpsons," color printouts of pictures of McCain and Obama, with handwritten labels reading "this one" and "that one," and two color prints of an actor who looked to me a bit like Hugh Grant. There were also old VHS tapes, an unused fireplace, a stationary exercise bike, and a large flat-screen television whose newness had no visible companion. Deutsch offered me tea and biscuits. I asked him about the Hugh Grant look-alike.

"You obviously don't watch much television," he replied. The man in the photographs was Hugh Laurie, a British actor known for his role in the American medical show "House." Deutsch described "House" to me as "a great program about epistemology, which, apart from fundamental physics, is really my core interest. It's a program about the myriad ways that knowledge can grow or can fail to grow." Dr. House is based on Sherlock Holmes, Deutsch informed me. "And House has a friend, Wilson, who is based on Watson. Like Holmes, House is an arch-rationalist. Everything's got to have a reason, and if he doesn't know the reason it's because he doesn't know it, not because there isn't one. That's an essential attitude in fundamental science." One imagines the ghost of Bohr would disagree.

Deutsch's reputation as a cloistered genius stems in large part from his foundational work in quantum computing. Since the nineteen-thirties, the field of computer science has held on to the idea of a universal computer, a notion first worked out by the field's modern founder, the British polymath Alan Turing. A universal computer would be capable of comporting itself as any other computer, just as a synthesizer can make the sounds made by any other musical instrument. In a 1985 paper, Deutsch pointed out that, because Turing was working with classical physics, his universal computer could imitate only a subset of possible computers. Turing's theory needed to account for quantum mechanics if its logic was to hold. Deutsch proposed a universal computer based on quantum physics, which would have calculating powers that Turing's computer (even in theory) could not simulate.

According to Deutsch, the insight for that paper came from a conversation in the early eighties with the physicist Charles Bennett, of I.B.M., about computational-complexity theory, at the time a sexy new field that investigated the difficulty of a computational task. Deutsch questioned whether computational complexity was a fundamental or a relative property. Mass, for instance, is a fundamental property, because it remains the same in any setting; weight is a relative property, because an object's weight depends on the strength of gravity acting on it. Identical baseballs on Earth and on the moon have equivalent masses, but different weights. If computational complexity was like mass—if it was a fundamental property—then complexity was quite profound; if not, then not.

“I was just sounding off,” Deutsch said. “I said they make too much of this”—meaning complexity theory—“because there’s no standard computer with respect to which you should be calculating the complexity of the task.” Just as an object’s weight depends on the force of gravity in which it’s measured, the degree of computational complexity depended on the computer on which it was measured. One could find out how complex a task was to perform on a particular computer, but that didn’t say how complex a task was *fundamentally*, in reference to the universe. Unless there really was such a thing as a universal computer, there was no way a description of complexity could be fundamental. Complexity theorists, Deutsch reasoned, were wasting their time.

Deutsch continued, “Then Charlie said, quietly, ‘Well, the thing is, there *is* a fundamental computer. The fundamental computer is physics itself.’ “ That impressed Deutsch. Computational complexity was a fundamental property; its value referenced how complicated a computation was on that most universal computer, that of the physics of the world. “I realized that Charlie was right about that,” Deutsch said. “Then I thought, But these guys are using the wrong physics. They realized that complexity theory was a statement about physics, but they didn’t realize that it mattered whether you used the true laws of physics, or some approximation, i.e., classical physics.” Deutsch began rewriting Turing’s universal-computer work using quantum physics. “Some of the differences are very large,” he said. Thus, at least in Deutsch’s mind, the quantum universal computer was born.

A number of physics journals rejected some of Deutsch’s early quantum-computing work, saying it was “too philosophical.” When it was finally published, he said, “a handful of people kind of got it.” One of them was the physicist Artur Ekert, who had come to Oxford as a graduate student, and who told me, “David was really the first one who formulated the concept of a quantum computer.”

Other important figures early in the field included the reclusive physicist Stephen J. Wiesner, who, with Bennett’s encouragement, developed ideas like quantum money (uncounterfeitable!) and quantum cryptography, and the philosopher of physics David Albert, whose imagining of introspective quantum automata (think robots in analysis) Deutsch describes in his 1985 paper as an example of “a true quantum computer.” Ekert says of the field, “We’re a bunch of odd ducks.”

Although Deutsch was not formally Ekert’s adviser, Ekert studied with him. “He kind of adopted me,” Ekert recalled, “and then, afterwards, I kind of adopted him. My tutorials at his place would start at around 8 P.M., when David would be having his lunch. We’d stay talking and working until the wee hours of the morning. He likes just talking things over. I would leave at 3 or 4 A.M., and then David would start properly working afterwards. If we came up with something, we would write the paper, but sometimes we wouldn’t write the paper, and if someone else also came up with the solution we’d say, ‘Good, now we don’t have to write it up.’ “ It was not yet clear, even in theory, what a quantum computer might be better at than a classical computer, and so Deutsch and Ekert tried to develop algorithms for problems that were intractable on a classical computer but that might be tractable on a quantum one.

One such problem is prime factorization. A holy grail of mathematics for centuries, it is the basis of much current cryptography. It’s easy to take two large prime numbers and multiply them, but it’s very difficult to take a large number that is the product of two primes and then deduce what the original prime factors are. To factor a number of two hundred digits or more would take a regular computer many lifetimes. Prime factorization is an example of a process that is easy one way (easy to scramble eggs) and very difficult the other (nearly impossible to unscramble them). In cryptography, two large prime numbers are multiplied to create a security key. Unlocking that key would be the equivalent of unscrambling an egg. Using prime factorization in this way is called RSA encryption (named for the scientists who proposed it, Rivest, Shamir, and Adleman), and it's how most everything is kept secret on the Internet, from your credit-card information to I.R.S. records.

In 1992, the M.I.T. mathematician Peter Shor heard a talk about theoretical quantum computing, which brought to his attention the work of Deutsch and other foundational thinkers in what was then still an obscure field. Shor worked on the factorization problem in private. "I wasn't sure anything would come of it," Shor explained. But, about a year later, he emerged with an algorithm that (a) could only be run on a quantum computer, and (b) could quickly find the prime factors of a very large number—the grail! With Shor's algorithm, calculations that would take a normal computer longer than the history of the universe would take a sufficiently powerful quantum computer an afternoon. "Shor's work was the biggest jump," the physicist David DiVincenzo, who is considered among the most knowledgeable about the history of quantum computing, says. "It was the moment when we were, like, Oh, now we see what it would be good for."

Today, quantum computation has the sustained attention of experimentalists; it also has serious public and private funding. Venture-capital companies are already investing in quantum encryption devices, and university research groups around the world have large teams working both to build hardware and to develop quantum-computer applications—for example, to model proteins, or to better understand the properties of superconductors.

Artur Ekert became a key figure in the transition from pure theory to building machines. He founded the quantum computation center at Oxford, as well as a similar center a few years later at Cambridge. He now leads a center in Singapore, where the government has made quantum-computing research one of its top goals. "Today in the field there's a lot of focus on lab implementation, on how and from what you could actually build a quantum computer," DiVincenzo said. "From the perspective of just counting, you can say that the majority of the field now is involved in trying to build some hardware. That's a result of the success of the field." In 2009, Google announced that it had been working on quantum-computing algorithms for three years, with the aim of having a computer that could quickly identify particular things or people from among vast stores of video and images—David Deutsch, say, from among millions of untagged photographs.

In the early nineteenth century, a "computer" was any person who computed: someone who did the math for building a bridge, for example. Around 1830, the English mathematician and inventor Charles Babbage worked out his idea for an Analytical Engine, a machine that would remove the human from computing, and thus bypass human error. Nearly no one imagined an analytical engine would be of much use, and in Babbage's time no such machine was ever built to completion. Though Babbage was prone to serious mental breakdowns, and though his bent of mind was so odd that he once wrote to Alfred Lord Tennyson correcting his math (Babbage suggested rewriting "Every minute dies a man / Every minute one is born" as "Every moment dies a man / Every moment one and a sixteenth is born," further noting that although the exact figure was 1.167, "something must, of course, be conceded to the laws of meter")—we can now say the guy was on to something.

A classical computer—any computer we know today—transforms an input into an output through nothing more than the manipulation of binary bits, units of information that can be either zero or one. A quantum computer is in many ways like a regular computer, but instead of bits it uses qubits. Each qubit (pronounced "Q-bit") can be zero or one, like a bit, but a qubit can also be zero *and* one—the quantum-mechanical quirk known as superposition. It is the state that the cat in the classic example of Schrödinger's closed box is stuck in: dead and alive at the same time. If one reads quantum-mechanical equations literally, superposition is ontological, not epistemological; it's not that we don't *know* which state the cat is in, but that the cat really *is* in both states at once. Superposition is like Freud's description of true ambivalence: not feeling unsure, but feeling opposing extremes of conviction at once. And, just as ambivalence holds more information than any single emotion, a qubit holds more information than a bit.

"Swim across the moat but keep the pizza dry."

What quantum mechanics calls entanglement also contributes to the singular powers of qubits. Entangled particles have a kind of E.S.P.: regardless of distance, they can instantly share information that an observer cannot even perceive is there. Input into a quantum computer can thus be dispersed among entangled qubits, which lets the processing of that information be spread out as well: tell one particle something, and it can instantly spread the word among all the other particles with which it's entangled.

There's information that we can't perceive when it's held among entangled particles; that information is their collective secret. As quantum mechanics has taught us, things are inexorably changed by our trying to ascertain anything about them. Once observed, qubits are no longer in a state of entanglement, or of superposition: the cat commits irrevocably to life or death, and this ruins the quantum computer's distinct calculating power. A quantum computer is the pot that, if watched, really won't boil. Charles Bennett described quantum information as being "like the information of a dream—we can't show it to others, and when we try to describe it we change the memory of it."

But, once the work on the problem has been done among the entangled particles, then we can look. When one turns to a quantum computer for an "answer," that answer, from having been held in that strange entangled way, among many particles, needs then to surface in just one, ordinary, unentangled place. That transition from entanglement to non-entanglement is sometimes termed "collapse." Once the system has collapsed, the information it holds is no longer a dream or a secret or a strange cat at once alive and dead; the answer is then just an ordinary thing we can read off a screen.

Qubits are not merely theoretical. Early work in quantum-computer hardware built qubits by manipulating the magnetic nuclei of atoms in a liquid soup with electrical impulses. Later teams, such as the one at Oxford, developed qubits using single trapped ions, a method that confines charged atomic particles to a particular space. These qubits are very precise, though delicate; protecting them from interference is quite difficult. More easily manipulated, albeit less precise, qubits have been built from superconducting materials arranged to model an atom. Typically, the fabrication of a qubit is not all that different from that of a regular chip. At Oxford, I saw something that resembled an oversize air-hockey table chaotically populated with a specialty Lego set, with what looked like a salad-bar sneeze guard hovering over it; this extended apparatus comprised lasers and magnetic-field generators and optical cavities, all arranged at just the right angles to manipulate and protect from interference the eight tiny qubits housed in a steel tube at the table's center.

Oxford's eight-qubit quantum computer has significantly less computational power than an abacus, but fifty to a hundred qubits could make something as powerful as any laptop. A team in Bristol, England, has a small, four-qubit quantum computer that can factor the number 15. A Canadian company claims to have built one that can do Sudoku, though that has been questioned by some who say that the processing is effectively being done by normal bits, without any superposition or entanglement.

Increasing the number of qubits, and thus the computer's power, is more than a simple matter of stacking. "One of the main problems with scaling up is a qubit's fidelity," Robert Schoelkopf, a physics professor at Yale who leads a quantum-computing team, explained. By fidelity, he refers to the fact that qubits "decohere"—fall out of their information-holding state—very easily. "Right now, qubits can be faithful for about a microsecond. And our calculations take about one hundred nanoseconds. Either calculations need to go faster or qubits need to be made more faithful."

What qubits are doing as we avert our gaze is a matter of some dispute, and occasionally—"shut up and calculate"—of some determined indifference, especially for more pragmatically minded physicists. For Deutsch, to really understand the workings of a quantum computer necessitates subscribing to Hugh Everett's Many Worlds Interpretation of quantum mechanics.

Everett's theory was neglected upon its publication, in 1957, and is still a minority view. It entails the following counterintuitive reasoning: every time there is more than one possible outcome, all of them occur. So if a radioactive atom might or might not decay at any given second, it both does and doesn't; in one universe it does, and in another it doesn't. These small branchings of possibility then ripple out until everything that is possible in fact *is*. According to Many Worlds theory, instead of a single history there are innumerable branchings. In one universe your cat has died, in another he hasn't, in a third you died in a sledding accident at age seven and never put your cat in the box in the first place, and so on.

Many Worlds is an ontologically extravagant proposition. But it also bears some comfortingly prosaic implications: in Many Worlds theory, science's aspiration to explain the world fully remains intact. The strangeness of superposition is, as Deutsch explains it, simply "the phenomenon of physical variables having different values in different universes." And entanglement, which so bothered Einstein and others, especially for its implication that particles could instantly communicate regardless of their distance in space or time, is also resolved. Information that seemed to travel faster than the speed of light and along no detectable pathway—spookily transmitted as if via E.S.P.—can, in Many Worlds theory, be understood to move differently. Information still spreads through direct contact—the "ordinary" way; it's just that we need to adjust to that contact being via the tangencies of abutting universes. As a further bonus, in Many Worlds theory randomness goes away, too. A ten-per-cent chance of an atom decaying is not arbitrary at all, but rather refers to the certainty that the atom will decay in ten per cent of the universes branched from that point. (This being science, there's the glory of nuanced dissent around the precise meaning of each descriptive term, from "chance" to "branching" to "universe.")

In the nineteen-seventies, Everett's theory received some of the serious attention it missed at its conception, but today the majority of physicists are not much compelled. "I've never myself subscribed to that view," DiVincenzo says, "but it's not a harmful view." Another quantum-computing physicist called it "completely ridiculous," but Ekert said, "Of all the weird theories out there, I would say Many Worlds is the least weird." In Deutsch's view, "Everett's approach was to look at quantum theory and see what it actually said, rather than hope it said certain things. What we want is for a theory to conform to reality, and, in order to find out whether it does, you need to see what the theory actually says. Which with the deepest theories is actually quite difficult, because they violate our intuitions."

I told Deutsch that I'd heard that even Everett thought his theory could never be tested.

"That was a catastrophic mistake," Deutsch said. "Every innovator starts out with the world view of the subject as it was before his innovation. So he can't be blamed for regarding his theory as an interpretation. But"—and here he paused for a moment—"I proposed a test of the Everett theory."

Deutsch posited an artificial-intelligence program run on a computer which could be used in a quantum-mechanics experiment as an "observer"; the A.I. program, rather than a scientist, would be doing the problematic "looking," and, by means of a clever idea that Deutsch came up with, a physicist looking at the A.I. observer would see one result if Everett's theory was right, and another if the theory was wrong.

It was a thought experiment, though. No A.I. program existed that was anywhere near sophisticated enough to act as the observer. Deutsch argued that theoretically there could be such a program, though it could only be run on radically more advanced hardware—hardware that could model any other hardware, including that of the human brain. The computer on which the A.I. program would run "had to have the property of being universal . . . so I had to postulate this quantum-coherent universal computer, and that was really my first proposal for a quantum computer. Though I didn't think of it as that. And I didn't call it a quantum computer. But that's what it was." Deutsch had, it seems, come up with the idea for a quantum computer twice: once in devising a way to test the validity of the Many Worlds Interpretation, and a second time, emerging from the complexity-theory conversation, with evidenced argument supporting Many Worlds as a consequence.

To those who find the Many Worlds Interpretation needlessly baroque, Deutsch writes, "the quantum theory of parallel universes is not the problem—it is the solution. . . . It is the explanation—the only one that is tenable—of a remarkable and counterintuitive reality." The theory also explains how quantum computers might work. Deutsch told me that a quantum computer would be "the first technology that allows useful tasks to be performed in collaboration between parallel universes." The quantum computer's processing power would come from a kind of outsourcing of work, in which calculations literally take place in other universes. Entangled particles would function as paths of communication among different universes, sharing information and gathering the results. So, for example, with the case of Shor's algorithm, Deutsch said, "When we run such an algorithm, countless instances of us are also running it in other universes. The computer then differentiates some of those universes (by creating a superposition) and as a result they perform part of the computation on a huge variety of different inputs. Later, those values affect each other, and thereby all contribute to the final answer, in just such a way that the same answer appears in all the universes."

Deutsch is mainly interested in the building of a quantum computer for its implications for fundamental physics, including the Many Worlds Interpretation, which would be a victory for the argument that science can explain the world and that, consequently, reality is knowable. ("House cures people," Deutsch said to me when discussing Hugh Laurie, "because he's interested in solving problems, not because he's interested in people.") Shor's algorithm excites Deutsch, but here is how his excitement comes through in his book "The Fabric of Reality":

> To those who still cling to a single-universe world-view, I issue this challenge: *explain how Shor's algorithm works*. I do not merely mean predict that it will work, which is merely a matter of solving a few uncontroversial equations. I mean provide an explanation. When Shor's algorithm has factorized a number, using 10^{500} or so times the computational resources than can be seen to be present, where was the number factorized? There are only about 10^{80} atoms in the entire visible universe, an utterly minuscule number compared with 10^{500}. So if the visible universe were the extent of physical reality, physical reality would not even remotely contain the resources required to factorize such a large number. Who did factorize it, then? How, and where, was the computation performed?

Deutsch believes that quantum computing and Many Worlds are inextricably bound. He is nearly alone in this conviction, though many (especially around Oxford) concede that the construction of a sizable and stable quantum computer might be evidence in favor of the Everett interpretation. "Once there are actual quantum computers," Deutsch said to me, "and a journalist can go to the actual labs and ask how does that actual machine work, the physicists in question will then either talk some obfuscatory nonsense, or will explain it in terms of parallel universes. Which will be newsworthy. Many

Worlds will then become part of our culture. Really, it has nothing to do with making the computers. But psychologically it has everything to do with making them."

It's tempting to view Deutsch as a visionary in his devotion to the Many Worlds Interpretation, for the simple reason that he has been a visionary before. "Quantum computers should have been invented in the nineteen-thirties," he observed near the end of our conversation. "The stuff that I did in the late nineteen-seventies and early nineteen-eighties didn't use any innovation that hadn't been known in the thirties." That is straightforwardly true. Deutsch went on, "The question is why."

DiVincenzo offered a possible explanation. "Your average physicists will say, 'I'm not strong in philosophy and I don't really know what to think, and it doesn't matter.' " He does not subscribe to Many Worlds, but is reluctant to dismiss Deutsch's belief in it, partly because it has led Deutsch to come up with his important theories, but also because "quantum mechanics does have a unique place in physics, in that it does have a subcurrent of philosophy you don't find even in Newton's laws or gravity. But the majority of physicists say it's a quagmire they don't want to get into—they'd rather work out the implications of ideas; they'd rather calculate something."

At Yale, a team led by Robert Schoelkopf has built a two-qubit quantum computer. "Deutsch is an original thinker and those early papers remain very important," Schoelkopf told me. "But what we're doing here is trying to develop hardware, to see if these descriptions that theorists have come up with work." They have configured their computer to run what is known as a Grover's algorithm, one that deals with a four-card-monte type of question: Which hidden card is the queen? It's a sort of Shor's algorithm for beginners, something that a small quantum computer can take on.

The Yale team fabricates their qubit processor chips in house. "The chip is basically made of a very thin wafer of sapphire or silicon—something that's a good insulator—that we then lay a patterned film of superconducting metal on to form the wiring and qubits," Schoelkopf said. What they showed me was smaller than a pinkie nail and looked like a map of a subway system.

Schoelkopf and his colleague Michel Devoret, who leads a separate team, took me to a large room of black lab benches, inscrutable equipment, and not particularly fancy monitors. The aesthetic was inadvertent steampunk. The dust in the room made me sneeze. "We don't like the janitors to come sweep for fear they'll disturb something," Schoelkopf said.

The qubit chip is small, but its supporting apparatus is imposing. The largest piece of equipment is the plumbing of the very high-end refrigerator, which reduces the temperature around the two qubits to ten millidegrees above absolute zero. The cold improves the computer's fidelity. Another apparatus produces the microwave signals that manipulate the qubits and set them into any degree of superposition that an experimenter chooses.

Running this Grover's algorithm takes a regular computer three or fewer steps—if after checking the third card you still haven't found the queen, you know she is under the fourth card—and on average it takes 2.25 steps. A quantum computer can run it in just one step. This is because the qubits can represent different values at the same time. In the four-card-monte example, each of the cards is represented by one of four states: 0,0; 0,1; 1,0; 1,1.

Schoelkopf designates one of these states as the queen, and the quantum computer must determine which one. "The magic comes from the initial state of the computer," he explained. Both of the qubits are set up, via pulses of microwave radiation, in a superposition of zero and one, so that each qubit represents two states at once, and together the two qubits represent all four states.

"Information can, in a way, be holographically represented across the whole computer; that's what we exploit," Devoret explained. "This is a property you don't find in a classical information processor. A bit has to be in one state—it has to be here or there. It's useful to have the bit be everywhere."

Through superposition and entanglement, the computer simultaneously investigates each of the four possible queen locations. “Right now we only get the right answer eighty per cent of the time, and we find even that pretty exciting,” Schoelkopf said.

With Grover’s algorithm, or theoretically with Shor’s, calculations are performed in parallel, though not necessarily in parallel worlds. “It’s as if I had a gazillion classical computers that were all testing different prime factors at the same time,” Schoelkopf summarized. “You start with a well-defined state, and you end with a well-defined state. In between, it’s a crazy entangled state, but that’s fine.”

Schoelkopf emphasized that quantum mechanics is a funny system but that it really is correct. “These oddnesses, like superposition and entanglement—they seemed like limitations, but in fact they are exploitable resources. Quantum mechanics is no longer a new or surprising theory that should strike us as odd.”

Schoelkopf seemed to suggest that existential questions like those which Many Worlds poses might be, finally, simply impracticable. “If you have to describe a result in my lab in terms of the computing chip,” he continued, “plus the measuring apparatus, plus the computer doing data collection, plus the experimenter at the bench . . . at some point you just have to give up and say, Now quantum mechanics doesn’t matter anymore, now I just need a classical result. At some point you have to simplify, you have to throw out some of the quantum information.” When I asked him what he thought of Many Worlds and of “collapse” interpretations—in which “looking” provokes a shift from an entangled to an unentangled state—he said, “I have an alternate language which I prefer in describing quantum mechanics, which is that it should really be called Collapse of the Physicist.” He knows it’s a charming formulation, but he does mean something substantive in saying it. “In reality it’s about where to collapse the discussion of the problem.”

I thought Deutsch might be excited by the Yale team’s research, and I e-mailed him about the progress in building quantum computers. “Oh, I’m sure they’ll be useful in all sorts of ways,” he replied. “I’m really just a spectator, though, in experimental physics.”

Sir Arthur Conan Doyle never liked detective stories that built their drama by deploying clues over time. Conan Doyle wanted to write stories in which all the ingredients for solving the crime were there from the beginning, and in which the drama would be, as in the Poe stories that he cited as precedents, in the mental workings of his ideal ratiocinator. The story of quantum computing follows a Holmesian arc, since all the clues for devising a quantum computer have been there essentially since the discovery of quantum mechanics, waiting for a mind to properly decode them.

But writers of detective stories have not always been able to hew to the rationality of their idealized creations. Conan Doyle believed in “spiritualism” and in fairies, even as the most famed spiritualists and fairy photographers kept revealing themselves to be fakes. Conan Doyle was also convinced that his friend Harry Houdini had supernatural powers; Houdini could do nothing to persuade him otherwise. Conan Doyle just *knew* that there was a spirit world out there, and he spent the last decades of his life corralling evidence ex post facto to support his unshakable belief.

Physicists are ontological detectives. We think of scientists as wholly rational, open to all possible arguments. But to begin with a conviction and then to use one’s intellectual prowess to establish support for that conviction is a methodology that really *has* worked for scientists, including Deutsch. One could argue that he dreamed up quantum computing because he was devoted to the idea that science can explain the world. Deutsch would disagree.

In “The Fabric of Reality,” Deutsch writes, “I remember being told, when I was a small child, that in ancient times it was still possible to know *everything that was known*. I was also told that nowadays so much is known that no one could conceivably learn more than a tiny fraction of it, even in a long lifetime. The latter proposition surprised and disappointed me. In fact, I refused to believe it.” Deutsch’s life’s work has been an attempt to support that intuitive disbelief—a gathering of argument for a conviction he held because he just knew.

Deutsch is adept at dodging questions about where he gets his ideas. He joked to me that they came from going to parties, though I had the sense that it had been years since he’d been to one. He said, “I don’t like the style of science reporting that goes over that kind of thing. It’s misleading. So Brahms lived on black coffee and forced himself to write a certain number of lines of music a day. Look,” he went on, “I can’t stop you from writing an article about a weird English guy who thinks there are parallel universes. But I think that style of thinking is kind of a put-down to the reader. It’s almost like saying, If you’re not weird in these ways, you’ve got no hope as a creative thinker. That’s not true. The weirdness is only superficial.”

Talking to Deutsch can feel like a case study of reason following desire; the desire is to be a creature of pure reason. As he said in praise of Freud, “He did a good service to the world. He made it O.K. to speak about the mechanisms of the mind, some of which we may not be aware of. His actual theory was all false, there’s hardly a single true thing he said, but that’s not so bad. He was a pioneer, one of the first who tried to think about things rationally.” ◆

Spooked

What do we learn about science from a controversy in physics?

Adam Gopnik **November 30, 2015 Issue**

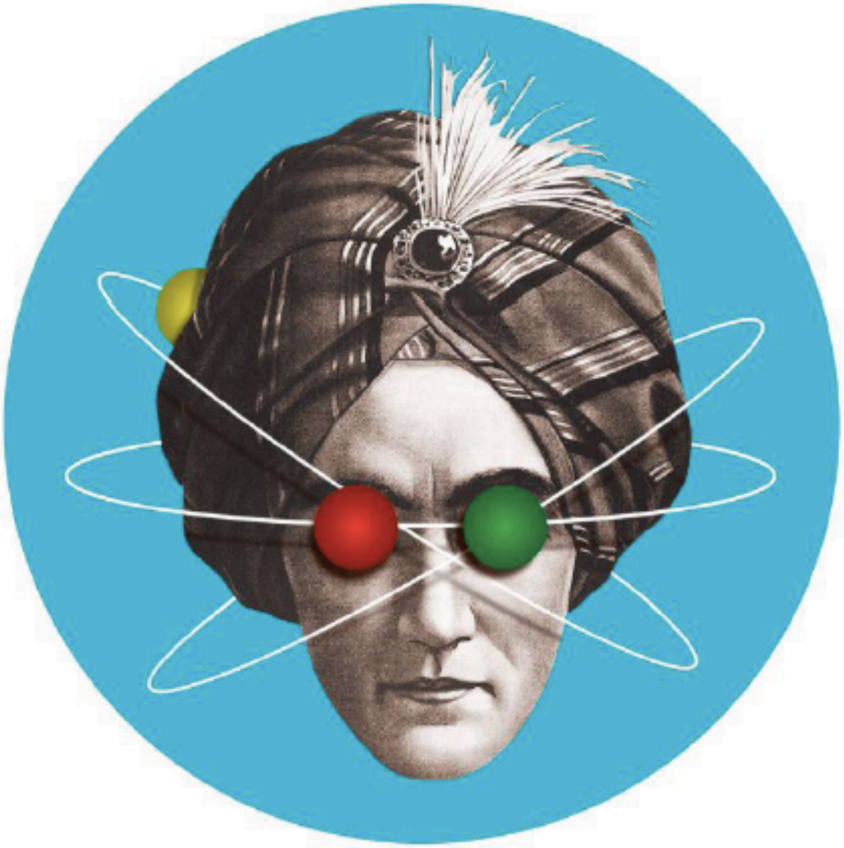

Illustration by Oliver Munday

What makes science science? The pious answers are: its ceaseless curiosity in the face of mystery, its keen edge of experimental objectivity, its endless accumulation of new data, and the cool machines it uses. We stare, the scientists see; we gawk, they gaze. We guess; they know.

But there are revisionist scholars who question the role of scientists as magi. Think how much we take on faith, even with those wonders of science that seem open to the non-specialist's eye. The proliferation of hominids—all those near-men and proto-men and half-apes found in the fossil record, exactly as Darwin predicted—rests on the interpretation of a few blackened Serengeti mandibles that it would take a lifetime's training to really evaluate. (And those who have put in the time end up squabbling anyway.)

Worse, small hints of what seems like scamming reach even us believers. Every few weeks or so, in the Science *Times,* we find out that some basic question of the universe has now been answered—but why, we wonder, weren't we told about the puzzle until after it was solved? Results announced as certain turn out to be hard to replicate. Triumphs look retrospectively engineered. This has led revisionist historians and philosophers to suggest that science *is* a kind of scam—a socially agreed-on fiction no more empirically grounded than any other socially agreed-on fiction, a faith like any other (as the defenders of faiths like any other like to say). Back when, people looked at old teeth and broken bones with the eye of faith and called them relics; we look at them with the eye of another faith and call them proof. What's different?

The defense of science against this claim turns out to be complicated, for the simple reason that, as a social activity, science is vulnerable to all the comedy inherent in any social activity: group thinking, self-pleasing, and running down the competition in order to get the customer's (or, in this case, the government's) cash. Books about the history of science should therefore be about both science and scientists, about the things they found and the way they found them. A good science writer has to show us the fallible men and women who made the theory, and then show us why, after the human foibles are boiled off, the theory remains reliable.

No well-tested scientific concept is more astonishing than the one that gives its name to a new book by the *Scientific American* contributing editor George Musser, "Spooky Action at a Distance" (Scientific American/Farrar, Straus & Giroux). The ostensible subject is the mechanics of quantum entanglement; the actual subject is the entanglement of its observers. Musser presents the hard-to-grasp physics of "non-locality," and his question isn't so much how this weird thing can be true as why, given that this weird thing had been known about for so long, so many scientists were so reluctant to confront it. What keeps a scientific truth from spreading?

The story dates to the early decades of quantum theory, in the nineteen-twenties and thirties, when Albert Einstein was holding out against the "probabilistic" views about the identity of particles and waves held by a younger generation of theoretical physicists. He created what he thought of as a reductio ad absurdum. Suppose, he said, that particles like photons and electrons really do act like waves, as the new interpretations insisted, and that, as they also insisted, their properties can be determined only as they are being measured. Then, he pointed out, something else would have to be true: particles that were part of a single wave function would be permanently "entangled," no matter how far from each other they migrated. If you have a box full of photons governed by one wave function, and one escapes, the escapee remains entangled in the fate of the particles it left behind—like the outer edges of the ripples spreading from a pebble thrown into a pond. An entangled particle, measured here in the Milky Way, would have to show the same spin—or the opposite spin, depending—or momentum as its partner, conjoined millions of light-years away, when measured at the same time. Like Paul Simon and Art Garfunkel, no matter how far they spread apart they would still be helplessly conjoined. Einstein's point was that such a phenomenon could only mean that the particles were somehow communicating with each other instantaneously, at a speed faster than light, violating the laws of nature. This was what he condemned as “spooky action at a distance.”

John Donne, thou shouldst be living at this hour! One can only imagine what the science-loving Metaphysical poet would have made of a metaphor that had two lovers spinning in unison no matter how far apart they were. But Musser has a nice, if less exalted, analogy for the event: it is as if two magic coins, flipped at different corners of the cosmos, always came up heads or tails together. (The spooky action takes place only in the context of simultaneous measurement. The particles share states, but they don’t send signals.)

What started out as a reductio ad absurdum became proof that the cosmos is in certain ways absurd. What began as a bug became a feature and is now a fact. Musser takes us into the lab of the Colgate professor Enrique Galvez, who has constructed a simple apparatus that allows him to entangle photons and then show that “the photons are behaving like a pair of magic coins. . . .They are not in contact, and no known force links them, yet they act as one.” With near-quantum serendipity, the publication of Musser’s book has coincided with news of another breakthrough experiment, in which scientists at Delft University measured two hundred and forty-five pairs of entangled electrons and confirmed the phenomenon with greater rigor than before. The certainty that spooky action at a distance takes place, Musser says, challenges the very notion of “locality,” our intuitive sense that some stuff happens only here, and some stuff over there. What’s happening isn’t really spooky action at a distance; it’s spooky distance, revealed through an action.

Why, then, did Einstein’s question get excluded for so long from reputable theoretical physics? The reasons, unfolding through generations of physicists, have several notable social aspects, worthy of Trollope’s studies of how private feuds affect public decisions. Musser tells us that fashion, temperament, zeitgeist, and sheer tenacity affected the debate, along with evidence and argument. The “indeterminacy” of the atom was, for younger European physicists, “a lesson of modernity, an antidote to a misplaced Enlightenment trust in reason, which German intellectuals in the 1920’s widely held responsible for their country’s defeat in the First World War.” The tonal and temperamental difference between the scientists was as great as the evidence they called on.

Musser tracks the action at the “Solvay” meetings, scientific conferences held at an institute in Brussels in the twenties. (Ernest Solvay was a rich Belgian chemist with a taste for high science.) Einstein and Niels Bohr met and argued over breakfast and dinner there, talking past each other more than to each other. Musser writes, “Bohr punted on Einstein’s central concern about links between distant locations in space,” preferring to focus on the disputes about probability and randomness in nature. As Musser says, the “indeterminacy” questions of whether what you measured was actually indefinite or just unknowable until you measured it was an important point, but not *this* important point.

Musser explains that the big issue was settled mainly by being pushed aside. Generational imperatives trumped evidentiary ones. The things that made Einstein the lovable genius of popular imagination were also the things that made him an easy object of condescension. The hot younger theorists patronized him, one of Bohr’s colleagues sneering that if a student had raised Einstein’s objections “I would have considered him quite intelligent and promising.”

There was never a decisive debate, never a hallowed crucial experiment, never even a winning argument to settle the case, with one physicist admitting, “Most physicists (including me) accept that Bohr won the debate, although like most physicists I am hard pressed to put into words just how it was done.” Arguing about non-locality went out of fashion, in this account, almost the way “Rock Around the Clock” displaced Sinatra from the top of the charts.

The same pattern of avoidance and talking-past and taking on the temper of the times turns up in the contemporary science that has returned to the possibility of non-locality. Musser notes that Geoffrey Chew's attack on the notion of underlying laws in physics "was radical, and radicalism went over well in '60's-era Berkeley." The British mathematician Roger Penrose's assaults on string theory in the nineties were intriguing but too intemperate and too inconclusive for the room: "Penrose didn't help his cause with his outspoken skepticism. . . . Valid though his critiques might have been, they weren't calculated to endear him to his colleagues."

Indeed, Musser, though committed to empirical explanation, suggests that the revival of "non-locality" as a topic in physics may be due to our finding the metaphor of non-locality ever more palatable: "Modern communications technology may not technically be non-local but it sure feels that it is." Living among distant connections, where what happens in Bangalore happens in Boston, we are more receptive to the idea of such a strange order in the universe. Musser sums it up in an enviable aphorism: "If poetry is emotion recollected in tranquility, then science is tranquility recollected in emotion." The seemingly neutral order of the natural world becomes the sounding board for every passionate feeling the physicist possesses.

Is science, then, a club like any other, with fetishes and fashions, with schemers, dreamers, and blackballed applicants? Is there a real demarcation to be made between science and every other kind of social activity? One of Musser's themes is that the boundary between inexplicable-seeming magical actions and explicable physical phenomena is a fuzzy one. The lunar theory of tides is an instance. Galileo's objection to it was like Einstein's to the quantum theory: that the moon working an occult influence on the oceans was obviously magical nonsense. This objection became Newton's point: occult influences could be understood soberly and would explain the movement of the stars and planets. What was magic became mathematical and then mundane. "Magical" explanations, like spooky action, are constantly being revived and rebuffed, until, at last, they are reinterpreted and accepted.

Instead of a neat line between science and magic, then, we see a jumpy, shifting boundary that keeps getting redrawn. It's like the "Looney Tunes" cartoon where Bugs draws a line in the dirt and dares Yosemite Sam to "just cross over dis line"—and then, when Sam does, Bugs redraws it, over and over, ever backward, until, in the end, Sam steps over a cliff. Real-world demarcations between science and magic, Musser's story suggests, are like Bugs's: made on the move and as much a trap as a teaching aid.

In the past several decades, certainly, the old lines between the history of astrology and astronomy, and between alchemy and chemistry, have been blurred; historians of the scientific revolution no longer insist on a clean break between science and earlier forms of magic. Where once logical criteria between science and non-science (or pseudo-science) were sought and taken seriously—Karl Popper's criterion of "falsifiability" was perhaps the most famous, insisting that a sound theory could, in principle, be proved wrong by one test or another—many historians and philosophers of science have come to think that this is a naïve view of how the scientific enterprise actually works. They see a muddle of coercion, old magical ideas, occasional experiment, hushed-up failures—all coming together in a social practice that gets results but rarely follows a definable logic.

Yet the old notion of a scientific revolution that was really a revolution is regaining some credibility. David Wootton, in his new, encyclopedic history, "The Invention of Science" (Harper), recognizes the blurred lines between magic and science but insists that the revolution lay in the public nature of the new approach. "What killed alchemy was not experimentation," he writes. He goes on:

> What killed alchemy was the insistence that experiments must be openly reported in publications which presented a clear account of what had happened, and they must then be replicated, preferably before independent witnesses. The alchemists had pursued a secret learning, convinced that only a few were fit to have knowledge of divine secrets and

> that the social order would collapse if gold ceased to be in short supply. . . . Esoteric knowledge was replaced by a new form of knowledge, which depended both on publication and on public or semi-public performance. A closed society was replaced by an open one.

In a piquant way, Wootton, while making little of Popper's criterion of falsifiability, makes it up to him by borrowing a criterion from his political philosophy. Scientific societies are open societies. One day the lunar tides are occult, the next day they are science, and what changes is the way in which we choose to talk about them.

Wootton also insists, against the grain of contemporary academia, that single observed facts, what he calls "killer facts," really did polish off antique authorities. Facts are not themselves obvious: the fact of the fact had to be invented, litigated, and re-litigated. But, once we agree that the facts *are* facts, they can do amazing work. Traditional Ptolemaic astronomy, in place for more than a millennium, was destroyed by what Galileo discovered about the phases of Venus. That killer fact "serves as a single, solid, and strong argument to establish its revolution around the Sun, such that no room whatsoever remains for doubt," Galileo wrote, and Wootton adds, "No one was so foolish as to dispute these claims." Observation was theory-soaked—Wootton shows a delightful drawing of a crater on the moon that does not actually exist, drawn by a dutiful English astronomer who had just been reading Galileo—and facts were, as always, tempered by our desires. But there they were, all the same, smiling fiendishly, like cartoon barracudas, as they ate up old orbits.

Several things flow from Wootton's view. One is that "group think" in the sciences is often true think. Science has always been made in a cloud of social networks. But this power of assent is valuable only if there's a willingness to look a killer fact in the eye. The Harvard theoretical physicist Lisa Randall's new book, "Dark Matter and the Dinosaurs" (Ecco), has as its arresting central thesis the idea that a disk of dark matter might exist in the Milky Way, perturbing the orbits of comets and potentially sending them periodically toward Earth, where they are likely to produce large craters and extinctions. But the theory is plausible only because a single killer fact murdered an earlier theory—which held that an unseen star was out there, doing the perturbing and the extincting. Every newer orbiting telescope has scanned the skies, and the so-called Nemesis star hasn't shown up. Disks of dark matter can now appear in the space left empty by the star's absence.

A similar pattern is apparent in the case of the search for "Vulcan," the hypothesized planet that, in the nineteenth century, sat between Mercury and the sun and explained perturbations in Mercury's orbit. As Thomas Levenson explains in "The Hunt for Vulcan" (Random House), nineteenth-century astronomers were so in love with the idea of the missing planet that many of them, bewitched by random shadows, insisted they had seen it through their telescopes. Only in 1915, when Einstein emerged with a new interpretation of the perturbations (something to do with gravity as space-time curvature), could astronomers stop "seeing" what wasn't there.

There has been much talk in the pop-sci world of "memes"—ideas that somehow manage to replicate themselves in our heads. But perhaps the real memes are not ideas or tunes or artifacts but ways of making them—*habits* of mind rather than *products* of mind. Science isn't a slot machine, where you drop in facts and get out truths. But it is a special kind of social activity, one where lots of different human traits—obstinacy, curiosity, resentment of authority, sheer cussedness, and a grudging readiness to submit pet notions to popular scrutiny—end by producing reliable knowledge. The spread of Bill James's ideas on baseball, from mimeographed sheets to the front offices of the Red Sox, is a nice instance of how a scientific turn of mind spread to a place where science hadn't usually gone. (James himself knew it, remarking that if he was going to be Galileo someone had to be the Pope.)

One way or another, science really happens. The claim that basic research is valuable because it leads to applied technology may be true but perhaps is not at the heart of the social use of the enterprise. The way scientists do think makes us aware of how we *can* think. Samuel Johnson said that a performer riding on three horses may not accomplish anything, but he increases our respect for the faculties of man. The scientists who show that nature rides three horses at once—or even two horses, on opposite sides of the universe—also widen our respect for what we are capable of imagining, and it is this action, at its own spooky distance, that really entangles our minds. ◆

Why We Don’t Believe In Science

Jonah Lehrer June 7, 2012

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Last week, Gallup announced the results of their latest survey on Americans and evolution. The numbers were a stark blow to high-school science teachers everywhere: forty-six per cent of adults said they believed that “God created humans in their present form within the last 10,000 years.” Only fifteen per cent agreed with the statement that humans had evolved without the guidance of a divine power.

What’s most remarkable about these numbers is their stability: these percentages have remained virtually unchanged since Gallup began asking the question, thirty years ago. In 1982, forty-four per cent of Americans held strictly creationist views, a statistically insignificant difference from 2012. Furthermore, the percentage of Americans that believe in biological evolution has only increased by four percentage points over the last twenty years.

Such poll data raises questions: Why are some scientific ideas hard to believe in? What makes the human mind so resistant to certain kinds of facts, even when these facts are buttressed by vast amounts of evidence?

A new study in *Cognition*, led by Andrew Shtulman at Occidental College, helps explain the stubbornness of our ignorance. As Shtulman notes, people are not blank slates, eager to assimilate the latest experiments into their world view. Rather, we come equipped with all sorts of naïve intuitions about the world, many of which are untrue. For instance, people naturally believe that heat is a kind of substance, and that the sun revolves around the earth. And then there's the irony of evolution: our views about our own development don't seem to be evolving.

This means that science education is not simply a matter of learning new theories. Rather, it also requires that students *unlearn* their instincts, shedding false beliefs the way a snake sheds its old skin.

To document the tension between new scientific concepts and our pre-scientific hunches, Shtulman invented a simple test. He asked a hundred and fifty college undergraduates who had taken multiple college-level science and math classes to read several hundred scientific statements. The students were asked to assess the truth of these statements as quickly as possible.

To make things interesting, Shtulman gave the students statements that were both intuitively and factually true ("The moon revolves around the Earth") and statements whose scientific truth contradicts our intuitions ("The Earth revolves around the sun").

As expected, it took students much longer to assess the veracity of true scientific statements that cut against our instincts. In every scientific category, from evolution to astronomy to thermodynamics, students paused before agreeing that the earth revolves around the sun, or that pressure produces heat, or that air is composed of matter. Although we know these things are true, we have to push back against our instincts, which leads to a measurable delay.

What's surprising about these results is that even after we internalize a scientific concept—the vast majority of adults now acknowledge the Copernican truth that the earth is not the center of the universe—that primal belief lingers in the mind. We never fully unlearn our mistaken intuitions about the world. We just learn to ignore them.

Shtulman and colleagues summarize their findings:

> When students learn scientific theories that conflict with earlier, naïve theories, what happens to the earlier theories? Our findings suggest that naïve theories are suppressed by scientific theories but not supplanted by them.

While this new paper provides a compelling explanation for why Americans are so resistant to particular scientific concepts—the theory of evolution, for instance, contradicts both our naïve intuitions and our religious beliefs—it also builds upon previous research documenting the learning process inside the head. Until we understand why some people believe in science we will never understand why most people don't.

In a 2003 study, Kevin Dunbar, a psychologist at the University of Maryland, showed undergraduates a few short videos of two different-sized balls falling. The first clip showed the two balls falling at the same rate. The second clip showed the larger ball falling at a faster rate. The footage was a reconstruction of the famous (and probably apocryphal) experiment performed by Galileo, in which he dropped cannonballs of different sizes from the Tower of Pisa. Galileo's metal balls all landed at the exact same time—a refutation of Aristotle, who claimed that heavier objects fell faster.

While the students were watching the footage, Dunbar asked them to select the more accurate representation of gravity. Not surprisingly, undergraduates without a physics background disagreed with Galileo. They found the two balls falling at the same rate to be deeply unrealistic. (Intuitively, we're all Aristotelians.) Furthermore, when Dunbar monitored the subjects in an fMRI machine, he found that showing non-physics majors the correct video triggered a particular pattern of brain activation: there was a squirt of blood to the anterior cingulate cortex, a collar of tissue located in the center of the brain. The A.C.C. is typically associated with the perception of errors and contradictions—neuroscientists often refer to it as part of the "Oh shit!" circuit—so it makes sense that it would be turned on when we watch a video of something that seems wrong, even if it's right.

This data isn't shocking; we already know that most undergrads lack a basic understanding of science. But Dunbar also conducted the experiment with physics majors. As expected, their education enabled them to identify the error; they knew Galileo's version was correct.

But it turned out that something interesting was happening inside their brains that allowed them to hold this belief. When they saw the scientifically correct video, blood flow increased to a part of the brain called the dorsolateral prefrontal cortex, or D.L.P.F.C. The D.L.P.F.C. is located just behind the forehead and is one of the last brain areas to develop in young adults. It plays a crucial role in suppressing so-called unwanted representations, getting rid of those thoughts that aren't helpful or useful. If you don't want to think about the ice cream in the freezer, or need to focus on some tedious task, your D.L.P.F.C. is probably hard at work.

According to Dunbar, the reason the physics majors had to recruit the D.L.P.F.C. is because they were busy suppressing their intuitions, resisting the allure of Aristotle's error. It would be so much more convenient if the laws of physics lined up with our naïve beliefs—or if evolution was wrong and living things didn't evolve through random mutation. But reality is not a mirror; science is full of awkward facts. And this is why believing in the right version of things takes work.

Of course, that extra mental labor isn't always pleasant. (There's a reason they call it "cognitive dissonance.") It took a few hundred years for the Copernican revolution to go mainstream. At the present rate, the Darwinian revolution, at least in America, will take just as long.

Illustration courtesy of Hulton Archive/Getty Images.

Helena Cronin

from THE ANT AND THE PEACOCK

■ **We now switch from physical science to my own subject of biology. Helena Cronin's beautifully written *The Ant and the Peacock* is mostly about two special problems that arose out of Darwin's work, altruism and sexual selection. But the book begins with as elegant a word picture as you'll find of the central idea of biology itself, Darwinian evolution.** ■

We are walking archives of ancestral wisdom. Our bodies and minds are live monuments to our forebears' rare successes. This Darwin has taught us. The human eye, the brain, our instincts, are legacies of natural selection's victories, embodiments of the cumulative experience of the past. And this biological inheritance has enabled us to build a new inheritance: a cultural ascent, the collective endowment of generations. Science is part of this legacy, and this book is about one of its foremost achievements: Darwinian theory itself.

[...]

A World Without Darwin

Imagine a world without Darwin. Imagine a world in which Charles Darwin and Alfred Russel Wallace had not transformed our understanding of living things. What, that is now comprehensible to us, would become baffling and puzzling? What would we see as in urgent need of explanation?

The answer is: practically everything about living things—about all of life on earth and for the whole of its history (and, probably, as we'll see, about life elsewhere, too). But there are two aspects of organisms that had baffled and puzzled people more than any others before Darwin and Wallace came up with their triumphant and elegant solution in the 1850s.

The first is design. Wasps and leopards and orchids and humans and slime moulds have a designed appearance about them; and so do eyes and kidneys and wings and pollen sacs; and so do colonies of ants, and flowers attracting bees to pollinate them, and a mother hen caring for her chicks. All this is in sharp contrast to rocks and stars and atoms and fire. Living things are beautifully and intricately adapted, and in myriad ways, to their inorganic surroundings, to other living things (not least to those most like themselves), and as superbly functioning wholes. They have an air of purpose about them, a highly organised complexity, a precision and efficiency. Darwin aptly referred to it as 'that perfection of structure and co-adaptation which most justly excites our admiration'. How has it come about?

The second puzzle is 'likeness in diversity'—the strikingly hierarchical relationships that can be found throughout the organic world, the differences and yet obvious similarities among groups of organisms, above all the links that bind the serried multitudes of species. By the mid-nineteenth century, these fundamental patterns had emerged from a range of biological disciplines. The fossil record was witness to continuity in time; geographical distribution to continuity in space; classification systems were built on what was called unity of type; morphology and embryology (particularly comparative studies) on so-called mutual affinities; and all these subjects revealed a remarkable abundance of further regularities and ever-more diversity. How could these relationships be accounted for? And whence such profligate speciation?

In the light of Darwinian theory, the answers to both questions, and to a host of other questions about the organic world, fall into place. Darwin and Wallace assumed that living things had evolved. Their problem was to find the mechanism by which this evolution had occurred, a mechanism that could account for both adaptation and diversity. Natural selection was their solution. Individuals vary and some of their variations are heritable. These heritable variations arise randomly—that is, independently of their effects on the survival and reproduction of the organism. But they are perpetuated differentially, depending on the adaptive advantage they confer.

Thus, over time, populations will come to consist of the better adapted organisms. And, as circumstances change, different adaptations become advantageous, gradually giving rise to divergent forms of life.

The key to all of this—to how natural selection is able to produce its wondrous results—is the power of many, many small but cumulative changes. Natural selection cannot jump from the primaeval soup to orchids and ants all in one go, at a single stroke. But it can get there through millions of small changes, each not very different from what went before but amounting over very long periods of time to a dramatic transformation. These changes arise randomly—without relation to whether they'll be good, bad or indifferent. So if they happen to be of advantage that's just a matter of chance. But it's not a grossly improbable chance, because the change is very small, from an organism that's not much like an exquisitely fashioned orchid to one that's ever-so-slightly more like it. So what would otherwise be a vast dollop of luck is smeared out into acceptably probable portions. And natural selection not only seizes on each of these chance advantages but also preserves them cumulatively, conserving them one after another throughout a vast series, until they gradually build up into the intricacy and diversity of adaptation that can move us to awed admiration. Natural selection's power, then, lies in randomly generated diversity that is pulled into line and shaped over vast periods of time by a selective force that is both opportunistic and conserving.

Colin Blakemore

from THE MIND MACHINE

■ The theme of eyes continues with the next extract by Colin Blakemore, British physiologist and head of the Medical Research Council, who always seems to me to be an incongruous (in the nicest possible way) combination of glamorous whiz kid and eminent elder statesman of science. The use of 'Grandma' as the object perceived in this hypothetical story of a photon is not as arbitrary as it sounds, by the way, but is an in-joke. Ever since the American neurophysiologist Jerry Lettvin epitomized highly specific pattern-detecting neurones as 'grandmother detectors', scientists have used 'Lettvin's grandmother' as an affectionate shorthand for the idea. It is Blakemore's witty tribute to Lettvin to use this vivid image without actually spelling out its history. ■

Sight Unseen

A single atom of gas, baking in the unimaginable heat at the surface of the sun, suddenly shifts from one energy state to another, and spits out the surplus energy as a photon—the smallest, indivisible unit of light. This tiny pellet of energy is thrown into space at the highest speed that Einstein could conceive of. Eight minutes or so after its birth, our chosen photon slows down a little as it hits the atmosphere of the Earth and a fraction of a second later it reaches the surface. It strikes the wrinkled skin of an old woman but, as chance has it, the wavelength of our charmed photon of light is such that it is not captured by the pigments of her skin. It is reflected, and 10 microseconds later it shoots into a tiny black hole, just 3 millimetres across. This hole is the pupil of a man's eye.

The photon slips past the transparent window that covers the front of his eye, through the lens within it and on, between the particles of the gelatinous mass behind the lens, even across the membranes and cytoplasm of the nerve cells of the retina in the back of the eye. But time is running out. It penetrates a strange, thin cell at the back of the retina and its existence ends as it strikes a single molecule of pigment inside that cell, which captures the photon, destroying it by stealing its energy.

'Hello, Grandma.' The man, whose retina has caught our hero, the photon, has recognised his grandmother. He sees her wrinkled face and her blue gingham dress.

She smiles and opens her mouth. As she exhales, the folds of her larynx vibrate as the air rushes past them. Her breath rushes around her moving tongue as it darts skilfully back and forth within her mouth, occasionally touching her lips or her teeth. She is speaking. The rich mixture of tones and noises pulses through the air towards her grandson's head. Some of the vibrating particles in the air are caught by the crevices of his outer ear and funnelled into the narrow tube that leads to his eardrum. They beat on it, setting up a rhythm in a chain of minute bones, which rattle at another membrane, setting up waves in the liquid inside a tiny coiled tube. And these vibrations, in turn, tickle hairs on tiny specialised nerve cells that stand like a regiment of sharp-eared soldiers along the length of the tube. 'Hello dear.' The man hears his grandmother speaking.

This everyday scene sets the stage for a detective story. The detective is the human brain; the story is our perception of the world around us.

KNOWLEDGE FROM MOLECULES AND WAVES

To the inner eye and ear of the conscious mind, our senses give us windows through which we see, hear, touch, taste, and smell the physical

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Arthur Eddington

from THE EXPANDING UNIVERSE

■ The first section of this book was on science's subject matter, and we began with the astronomer Sir James Jeans. In the second section we turn to scientists themselves and the nature of science, beginning with Jeans's near contemporary Sir Arthur Eddington. Their names are often bracketed together, as eminent astronomers of the early twentieth century who went out of their way to communicate the romance of their subject to the interested public. Eddington is also famous for his expedition to the island of Principe in 1919 to exploit the total eclipse of the sun and make observations of a distant star to test Einstein's general theory of relativity (see also Paul Davies, below). The prediction was confirmed, and Eddington was able to announce to the world, in Banesh Hoffman's phrase, that Germany was host to the greatest scientist of the age. Einstein himself is reported to have been indifferent to Eddington's dramatic vindication. Any other result, and he would have been '. . . sorry for the dear Lord. The theory is correct.' Perhaps Einstein should have been more ready, in the words of this extract from Eddington's *The Expanding Universe*, 'to see what is going on in the workshops' of science, rather than to rely on his aesthetic intuition, amazingly gifted though it was. ■

Now I have told you 'everything right as it fell out'.

How much of the story are we to believe?

Science has its showrooms and its workshops. The public today, I think rightly, is not content to wander round the showrooms where the tested products are exhibited; the demand is to see what is going on in the workshops. You are welcome to enter; but do not judge what you see by the standards of the showroom.

We have been going round a workshop in the basement of the building of science. The light is dim, and we stumble sometimes. About us is confusion and mess which there has not been time to sweep away. The workers and their machines are enveloped in murkiness. But I think that something is being shaped here—perhaps something rather big. I do not quite know what it will be when it is completed and polished for the showroom. But we can look at the present designs and the novel tools that are being used in its manufacture; we can contemplate too the little successes which make us hopeful.

A slight reddening of the light of distant galaxies, an adventure of the mathematical imagination in spherical space, reflections on the underlying principles implied in all measurement, nature's curious choice of certain numbers such as 137 in her scheme—these and many other scraps have come together and formed a vision. As when the voyager sights a distant shore, we strain our eyes to catch the vision. Later we may more fully resolve its meaning. It changes in the mist; sometimes we seem to focus the substance of it, sometimes it is rather a vista leading on and on till we wonder whether aught can be final.

Once more I have recourse to Bottom the weaver—

> I have had a most rare vision. I have had a dream, past the wit of man to say what dream it was: man is but an ass, if he go about to expound this dream.…Methought I was,—and methought I had,—but man is but a patched fool, if he will offer to say what methought I had.…
>
> It shall be called Bottom's Dream, because it hath no bottom.

Oliver Sacks

from UNCLE TUNGSTEN

■ Oliver Sacks is best known as a sympathetic clinical neurologist with a wonderful portfolio of unsettling case histories and a gift for recounting and drawing lessons from them. But he himself was first drawn to science by a love of chemistry, awakened by his mother's brother, 'Uncle Tungsten', surely the best sort of uncle any child could wish for. Sacks is still fascinated by chemistry, and this extract from his *Uncle Tungsten* well conveys the romantic pull that science can exert on an intelligent young mind. John Maynard Smith and I were once being shown around the Panama jungle as honoured guests by a young American researcher, and Maynard Smith whispered to me, 'Isn't it nice to listen to a man who really loves his animals.' The 'animals' in this case were trees. In Oliver Sacks's case they are elements, but the principle remains. ■

We had called him Uncle Tungsten for as long as I could remember, because he manufactured lightbulbs with filaments of fine tungsten wire.

His firm was called Tungstalite, and I often visited him in the old factory in Farringdon and watched him at work, in a wing collar, with his shirt-sleeves rolled up. The heavy, dark tungsten powder would be pressed, hammered, sintered at red heat, then drawn into finer and finer wire for the filaments. Uncle's hands were seamed with the black powder, beyond the power of any washing to get out (he would have to have the whole thickness of epidermis removed, and even this, one suspected, would not have been enough). After thirty years of working with tungsten, I imagined, the heavy element was in his lungs and bones, in every vessel and viscus, every tissue of his body. I thought of this as a wonder, not a curse—his body invigorated and fortified by the mighty element, given a strength and enduringness almost more than human.

Whenever I visited the factory, he would take me around the machines, or have his foreman do so. (The foreman was a short, muscular man, a Popeye with enormous forearms, a palpable testament to the benefits of working with tungsten.) I never tired of the ingenious machines, always beautifully clean and sleek and oiled, or the furnace where the black powder was compacted from a powdery incoherence into dense, hard bars with a grey sheen.

During my visits to the factory, and sometimes at home, Uncle Dave would teach me about metals with little experiments. I knew that mercury, that strange liquid metal, was incredibly heavy and dense. Even lead floated on it, as my uncle showed me by floating a lead bullet in a bowl of quicksilver. But then he pulled out a small grey bar from his pocket, and to my amazement, this sank immediately to the bottom. That, he said, was *his* metal, tungsten.

Uncle loved the density of the tungsten he made, and its refractoriness, its great chemical stability. He loved to handle it—the wire, the powder, but the massy little bars and ingots most of all. He caressed them, balanced them (tenderly, it seemed to me) in his hands. 'Feel it, Oliver,' he would say, thrusting a bar at me. 'Nothing in the world feels like sintered tungsten.' He would tap the little bars and they would emit a deep clink. 'The sound of tungsten,' Uncle Dave would say, 'nothing like it.' I did not know whether this was true, but I never questioned it.

[…]

Uncle Dave loved handling the metals and minerals in his cabinet, allowing me to handle them, expatiating on their wonders. He saw the whole earth, I think, as a gigantic natural laboratory, where heat and pressure caused not only vast geologic movements, but innumerable chemical miracles too. 'Look at these diamonds,' he would say, showing me a specimen from the famous Kimberley mine. 'They are almost as old as the earth. They were formed thousands of millions of years ago, deep in the earth, under unimaginable pressures. Then they were brought to the surface in this kimberlite, tracking hundreds of miles from the earth's mantle, and then through the crust, till they finally reached the surface. We may never see the interior of the earth directly, but this kimberlite and its diamonds are a sample of what it is like. People have tried to manufacture diamonds,' he added, 'but we cannot match the temperatures and pressures that are necessary.'[1]

On one visit, Uncle Dave showed me a large bar of aluminum. After the dense platinum metals, I was amazed at how light it was, scarcely heavier than a piece of wood. 'I'll show you something interesting', he said. He took a smaller lump of aluminum, with a smooth, shiny surface, and smeared it with mercury. All of a sudden—it was like some terrible disease—the surface broke down, and a white substance like a fungus rapidly grew out of it, until it was a quarter of an inch high, then half an inch high, and it kept growing and growing until the aluminum was completely eaten up. 'You've seen iron rust—oxidizing, combining with the oxygen in the air', Uncle said. 'But here, with the aluminum, it's a million times faster. That big bar is still quite shiny, because it's covered by a fine layer of oxide, and that protects it from further change. But rubbing it with mercury destroys the surface layer, so then the aluminum has no protection, and it combines with the oxygen in seconds.'

I found this magical, astounding, but also a little frightening—to see a bright and shiny metal reduced so quickly to a crumbling mass of oxide. It made me think of a curse or a spell, the sort of disintegration I sometimes saw in my dreams. It made me think of mercury as evil, as a destroyer of metals. Would it do this to every sort of metal?

'Don't worry,' Uncle answered, 'the metals we use here, they're perfectly safe. If I put this little bar of tungsten in the mercury, it would not be affected at all. If I put it away for a million years, it would be just as bright and shiny as it is now.' The tungsten, at least, was stable in a precarious world.

'You've seen,' Uncle Dave went on, 'that when the surface layer is broken, the aluminum combines very rapidly with oxygen in the air to form this white oxide, which is called alumina. It is similar with iron as it rusts; rust is an iron oxide. Some metals are so avid for oxygen that they will combine with it, tarnishing, forming an oxide, the moment they are exposed to the air. Some will even pull the oxygen out of water, so one has to keep them in a sealed tube or under oil.' Uncle showed me some chunks of metal with a whitish surface, in a bottle of oil. He fished out a chunk and cut it with his penknife. I was amazed at how soft it was; I had never seen a metal cut like this. The cut surface had a brilliant, silvery luster. This was calcium, Uncle said, and it was so active that it never occurred in nature as the pure metal, but only as compounds or minerals from which it had to be extracted. The white cliffs of Dover, he said, were chalk; others were made of limestone—these were different forms of calcium carbonate, a major component in the crust of the earth. The calcium metal, as we spoke, had oxidized completely, its bright surface now a dull, chalky white. 'It's turning into lime,' Uncle said, 'calcium oxide.'

But sooner or later Uncle's soliloquies and demonstrations before the cabinet all returned to *his* metal. 'Tungsten,' he said. 'No one realized at first how perfect a metal it was. It has the highest melting point of any metal, it is tougher than steel, and it keeps its strength at high temperatures—an ideal metal!'

Uncle had a variety of tungsten bars and ingots in his office. Some he used as paperweights, but others had no discernible function whatever, except to give pleasure to their owner and maker. And indeed, by comparison, steel bars and even lead felt light and somehow porous, tenuous. 'These lumps of tungsten have an extraordinary concentration of mass', he would say. 'They would be deadly as weapons—far deadlier than lead.'

They had tried to make tungsten cannonballs at the beginning of the century, he added, but found the metal too hard to work—though they used it sometimes for the bobs of pendulums. If one wanted to weigh the earth, Uncle Dave suggested, and to use a very dense, compact mass to 'balance' against it, one could do no better than to use a huge sphere of tungsten. A ball only two feet across, he calculated, would weigh five thousand pounds.

One of tungsten's mineral ores, scheelite, Uncle Dave told me, was named after the great Swedish chemist Carl Wilhelm Scheele, who was

the first to show that it contained a new element. The ore was so dense that miners called it 'heavy stone' or *tung sten*, the name subsequently given to the element itself. Scheelite was found in beautiful orange crystals that fluoresced bright blue in ultraviolet light. Uncle Dave kept specimens of scheelite and other fluorescent minerals in a special cabinet in his office. The dim light of Farringdon Road on a November evening, it seemed to me, would be transformed when he turned on his Wood's lamp and the luminous chunks in the cabinet suddenly glowed orange, turquoise, crimson, green.

Though scheelite was the largest source of tungsten, the metal had first been obtained from a different mineral, called wolframite. Indeed, tungsten was sometimes called wolfram, and still retained the chemical symbol W. This thrilled me, because my own middle name was Wolf. Heavy seams of the tungsten ores were often found with tin ore, and the tungsten made it more difficult to isolate the tin. This was why, my uncle continued, they had originally called the metal wolfram—for, like a hungry animal, it 'stole' the tin. I liked the name *wolfram*, its sharp, animal quality, its evocation of a ravening, mystical wolf—and thought of it as a tie between Uncle Tungsten, Uncle Wolfram, and myself, O. Wolf Sacks.

[…]

Scheele was one of Uncle Dave's great heroes. Not only had he discovered tungstic acid and molybdic acid (from which the new element molybdenum was made), but hydrofluoric acid, hydrogen sulfide, arsine, and prussic acid, and a dozen organic acids, too. All this, Uncle Dave said, he did by himself, with no assistants, no funds, no university position or salary, but working alone, trying to make ends meet as an apothecary in a small provincial Swedish town. He had discovered oxygen, not by a fluke, but by making it in several different ways; he had discovered chlorine; and he had pointed the way to the discovery of manganese, of barium, of a dozen other things.

Scheele, Uncle Dave would say, was wholly dedicated to his work, caring nothing for fame or money and sharing his knowledge, whatever he had, with anyone and everyone. I was impressed by Scheele's generosity, no less than his resourcefulness, by the way in which (in effect) he gave the actual discovery of elements to his students and friends—the discovery of manganese to Johan Gahn, the discovery of molybdenum to Peter Hjelm, and the discovery of tungsten itself to the d'Elhuyar brothers.

Scheele, it was said, never forgot anything if it had to do with chemistry. He never forgot the look, the feel, the smell of a substance, or the way it was transformed in chemical reactions, never forgot anything he read, or was told, about the phenomena of chemistry. He seemed indifferent, or inattentive, to most things else, being wholly dedicated to his single passion, chemistry. It was this pure and passionate absorption in phenomena—noticing everything, forgetting nothing—that constituted Scheele's special strength.

Scheele epitomized for me the romance of science. There seemed to me an integrity, an essential goodness, about a life in science, a lifelong love affair. I had never given much thought to what I might be when I was 'grown up'—growing up was hardly imaginable—but now I knew: I wanted to be a chemist. A chemist like Scheele, an eighteenth-century chemist coming fresh to the field, looking at the whole undiscovered world of natural substances and minerals, analyzing them, plumbing their secrets, finding the wonder of unknown and new metals.

1. There were many attempts to manufacture diamonds in the nineteenth century, the most famous being those of Henri Moissan, the French chemist who first isolated fluorine and invented the electrical furnace. Whether Moissan actually got any diamonds is doubtful—the tiny, hard crystals he took for diamond were probably silicon carbide (which is now called moissanite). The atmosphere of this early diamond-making, with its excitements, its dangers, its wild ambitions, is vividly conveyed in H. G. Wells's story 'The Diamond Maker'.

The Pulsating Universe

After dinner on their first evening in the Beach Hotel with the old professor talking about cosmology, and his daughter chatting about art, Mr Tompkins finally got to his room, collapsed on to the bed, and pulled the blanket over his head. Botticelli and Bondi, Salvador Dali and Fred Hoyle, Lemaître and La Fontaine got all mixed up in his tired brain, and finally he fell into a deep sleep....

Sometime in the middle of the night he woke up with a strange feeling that instead of lying on a comfortable spring mattress he was lying on something hard. He opened his eyes and found himself prostrated on what he first thought to be a big rock on the seashore. Later he discovered that it was actually a very big rock, about 30 feet in diameter, suspended in space without any visible support. The rock was covered with some green moss, and in a few places little bushes were growing from cracks in the stone. The space around the rock was illuminated by some glimmering light and was very dusty. In fact, there was more dust in the air than he had ever seen, even in the films representing dust storms in the middle west. He tied his handkerchief round his nose and felt, after this, considerably relieved. But there were more dangerous things than the dust in the surrounding space. Very often stones of the size of his head and larger were swirling through the space near his rock, occasionally hitting it with a strange dull sound of impact. He noticed also one or two rocks of approximately the same size as his own, floating through space at some distance away. All this time, inspecting his surroundings, he was clinging hard to some protruding edges of his rock in constant fear of falling off and being lost in the dusty depths below. Soon, however, he became bolder, and made an attempt to crawl to the edge of his rock and to see whether there was really nothing underneath, supporting it. As he was crawling in this way, he noticed, to his great surprise, that he did not fall off, but that his weight was constantly pressing him to the surface of the rock, although he had covered already more than a quarter of its circumference. Looking from behind a ridge of loose stones on the spot just underneath the place where he originally found himself, he discovered nothing to support the rock in space. To his great surprise, however, the glimmering light revealed the tall figure of his friend the old professor standing apparently with his head down and making some notes in his pocket-book.

Now Mr Tompkins began slowly to understand. He remembered that he was taught in his schooldays that the earth is a big round rock moving freely in space around the sun. He also remembered the picture of two antipodes standing on the opposite sides of the earth. Yes, his rock was just a very small stellar body attracting everything to its surface, and he and the old professor were the only population of this little planet. This consoled him a little; there was at least no danger of falling off!

'Good morning,' said Mr Tompkins, to divert the old man's attention from his calculations.

The professor raised his eyes from his note-book. 'There are no mornings here,' he said, 'there is no sun and not a single luminous star in this universe. It is lucky that the bodies here show some chemical process on their surface, otherwise I should not be able to observe the expansion of this space', and he returned again to his note-book.

Mr Tompkins felt quite unhappy; to meet the only living person in the whole universe, and to find him so unsociable! Unexpectedly, one of the little meteorites came to his help; with a crashing sound the stone hit the book in the hands of the professor and threw it, travelling fast through space, away from their little planet. 'Now you will never see it again,' said Mr Tompkins, as the book got smaller and smaller, flying through space.

'On the contrary,' replied the professor. 'You see, the space in which we now are is not infinite in its extension. Oh yes, yes, I know that you have been taught in school that space is infinite, and that two parallel lines never meet. This, however, is not true either for the space in which the rest of humanity lives, or for the space in which we are now. The first one is of course very large indeed; the scientists estimated its present dimensions to be about 10,000,000,000,000,000,000,000 miles, which, for an ordinary mind, is fairly infinite. If I had lost my book there, it would take an incredibly long time to come back. Here, however, the situation is rather different. Just before the note-book was torn out of my hands, I had figured out that this space is only about five miles in diameter, though it is rapidly expanding. I expect the book back in not more than half an hour.'

Figure 21. There are no mornings here.

'But,' ventured Mr Tompkins, 'do you mean that your book is going to behave like the boomerang of an Australian native, and, by moving along a curved trajectory, fall down at your feet?'

'Nothing of the sort,' answered the professor. 'If you want to understand what really happens, think about an ancient Greek who did not know that the earth was a sphere. Suppose he has given somebody instructions to go always straight northwards. Imagine his astonishment when his runner finally returns to him from the south. Our ancient Greek did not have a notion about travelling round the world (round the earth, I mean in this case), and he would be sure that his runner had lost his way and had taken a curved route which brought him back. In reality his man was going all the time along the straightest line one can draw on the surface of the earth, but he travelled round the world and thus came back from the opposite direction. The same thing is going to happen to my book, unless it is hit on its way by some other stone and thus deflected from the straight track. Here, take these binoculars, and see if you can still see it.'

Mr Tompkins put the binoculars to his eyes, and, through the dust which somewhat obscured the whole picture, he managed to see the professor's note-book travelling through space far far away. He was somewhat surprised by the pink colouring of all the objects, including the book, at that distance.

'But,' he exclaimed after a while, 'your book is returning, I see it growing larger.'

'No,' said the professor, 'it is still going away. The fact that you see it growing in size, as if it were coming back, is due to a peculiar focusing effect of the closed spherical space on the rays of light. Let us return to our ancient Greek. If the rays of light could be kept going all the time along the curved surface of the earth, let us say by refraction of the atmosphere, he would be able, using powerful binoculars, to see his runner all the time during the journey. If you look on the globe, you will see that the straightest lines on its surface, the meridians, first diverge from one pole, but, after passing the equator, begin to converge towards the opposite pole. If the rays of light travelled along the meridians, you, located, for example, at one pole, would see the person going away from you growing smaller and smaller only until he crossed the equator. After this point you would see him growing larger and it would seem to you that he was returning, going, however, backwards. After he had reached the opposite pole, you would see him as large as if he were standing right by your side. You would not be able, however, to touch him, just as you cannot touch the image in a spherical mirror. On this basis of two-dimensional analogy, you can imagine what happens to the light rays in the strangely curved three-dimensional space. Here, I think the image of the book is quite close now.' In fact, dropping the binoculars, Mr Tompkins could see that the book was only a few yards away. It looked, however, very strange indeed! The contours were not sharp, but rather washed out, the formulae written by the professor on its pages could be

hardly recognized, and the whole book looked like a photograph taken out of focus and underdeveloped.

'You see now,' said the professor, 'that this is only the image of the book, badly distorted by light travelling across one half of the universe. If you want to be quite sure of it, just notice how the stones behind the book can be seen through its pages.'

Mr Tompkins tried to reach the book, but his hand passed through the image without any resistance.

'The book itself,' said the professor, 'is now very close to the opposite pole of the universe, and what you see here are just two images of it. The second image is just behind you and when both images coincide, the real book will be exactly at the opposite pole.' Mr Tompkins didn't hear; he was too deeply absorbed in his thoughts, trying to remember how the images of objects are formed in elementary optics by concave mirrors and lenses. When he finally gave it up, the two images were again receding in opposite directions.

'But what makes the space curved and produce all these funny effects?' he asked the professor.

'The presence of ponderable matter,' was the answer. 'When Newton discovered the law of gravity, he thought that gravity was just an ordinary force, the same type of force as, for example, is produced by an elastic string stretched between two bodies. There always remains, however, the mysterious fact that all bodies, independent of their weight and size, have the same acceleration and move the same way under the action of gravity, provided you eliminate the friction of air and that sort of thing, of course. It was Einstein who first made it clear that the primary action of ponderable matter is to produce the curvature of space and that the trajectories of all bodies moving in the field of gravity are curved just because space itself is curved. But I think it is too hard for you to understand, without knowing sufficient mathematics.'

'It is,' said Mr Tompkins. 'But tell me, if there were no matter, would we have the kind of geometry I was taught at school, and would parallel lines never meet?'

'They would not,' answered the professor, 'but neither would there be any material creature to check it.'

Our character lies for hundreds of millions of years, bound to three atoms of oxygen and one of calcium, in the form of limestone: it already has a very long cosmic history behind it, but we shall ignore it. For it time does not exist, or exists only in the form of sluggish variations in temperature, daily or seasonal, if, for the good fortune of this tale, its position is not too far from the earth's surface. Its existence, whose monotony cannot be thought of without horror, is a pitiless alternation of hots and colds, that is, of oscillations (always of equal frequency) a trifle more restricted and a trifle more ample: an imprisonment, for this potentially living personage, worthy of the Catholic Hell. To it, until this moment, the present tense is suited, which is that of description, rather than the past tense, which is that of narration—it is congealed in an eternal present, barely scratched by the moderate quivers of thermal agitation.

But, precisely for the good fortune of the narrator, whose story could otherwise have come to an end, the limestone rock ledge of which the atom forms a part lies on the surface. It lies within reach of man and his pickax (all honor to the pickax and its modern equivalents; they are still the most important intermediaries in the millennial dialogue between the elements and man): at any moment—which I, the narrator, decide out of pure caprice to be the year 1840—a blow of the pickax detached it and sent it on its way to the lime kiln, plunging it into the world of things that change. It was roasted until it separated from the calcium, which remained so to speak with its feet on the ground and went to meet a less brilliant destiny, which we shall not narrate. Still firmly clinging to two of its three former oxygen companions, it issued from the chimney and took the path of the air. Its story, which once was immobile, now turned tumultuous.

It was caught by the wind, flung down on the earth, lifted ten kilometers high. It was breathed in by a falcon, descending into its precipitous lungs, but did not penetrate its rich blood and was expelled. It dissolved three times in the water of the sea, once in the water of a cascading torrent, and again was expelled. It traveled with the wind for eight years: now high, now low, on the sea and among the clouds, over forests, deserts, and limitless expanses of ice; then it stumbled into capture and the organic adventure.

Carbon, in fact, is a singular element: it is the only element that can bind itself in long stable chains without a great expense of energy, and for life on earth (the only one we know so far) precisely long chains are required. Therefore carbon is the key element of living substance: but its promotion, its entry into the living world, is not easy and must follow an obligatory, intricate path, which has been clarified (and not yet definitively) only in recent years. If the elaboration of carbon were not a common daily occurrence, on the scale of billions of tons a week, wherever the green of a leaf appears, it would by full right deserve to be called a miracle.

The atom we are speaking of, accompanied by its two satellites which maintained it in a gaseous state, was therefore borne by the wind along a row of vines in the year 1848. It had the good fortune to brush against a leaf, penetrate it, and be nailed there by a ray of the sun. If my language here becomes imprecise and allusive, it is not only because of my ignorance: this decisive event, this instantaneous work *a tre*—of the carbon dioxide, the light, and the vegetal greenery—has not yet been described in definitive terms, and perhaps it will not be for a long time to come, so different is it from that other 'organic' chemistry which is the cumbersome, slow, and ponderous work of man: and yet this refined, minute, and quick-witted chemistry was 'invented' two or three billion years ago by our silent sisters, the plants, which do not experiment and do not discuss, and whose temperature is identical to that of the environment in which they live. If to comprehend is the same as forming an image, we will never form an image of a happening whose scale is a millionth of a millimeter, whose rhythm is a millionth of a second, and whose protagonists are in their essence invisible. Every verbal description must be inadequate, and one will be as good as the next, so let us settle for the following description.

Our atom of carbon enters the leaf, colliding with other innumerable (but here useless) molecules of nitrogen and oxygen. It adheres to a large and complicated molecule that activates it, and simultaneously receives the decisive message from the sky, in the flashing form of a packet of solar light: in an instant, like an insect caught by a spider, it is separated from its oxygen, combined with hydrogen and (one thinks) phosphorus, and finally inserted in a chain, whether long or short does not matter, but it is the chain of life. All this happens swiftly, in silence, at the temperature and pressure of the atmosphere, and gratis: dear colleagues, when we learn to do likewise we will be *sicut Deus*, and we will have also solved the problem of hunger in the world.

But there is more and worse, to our shame and that of our art. Carbon dioxide, that is, the aerial form of the carbon of which we have up till now spoken: this gas which constitutes the raw material of life, the permanent store upon which all that grows draws, and the ultimate destiny of all flesh, is not one of the principal components of air but rather a ridiculous remnant, an 'impurity,' thirty times less abundant than argon, which nobody even notices. The air contains 0.03 per cent; if Italy was air, the only Italians fit to build life would be, for example, the fifteen thousand inhabitants of Milazzo in the province of Messina. This, on the human scale, is ironic acrobatics, a juggler's trick, an incomprehensible display of omnipotence-arrogance, since from this ever renewed impurity of the air we come, we animals and we plants, and we the human species, with our four billion discordant opinions, our millenniums of history, our wars and shames, nobility and pride. In any event, our very presence on the planet becomes laughable in geometric terms: if all of humanity, about 250 million tons, were distributed in a layer of homogeneous thickness on all the emergent lands, the 'stature of man' would not be visible to the naked eye; the thickness one would obtain would be around sixteen thousandths of a millimeter.

Now our atom is inserted: it is part of a structure, in an architectural sense; it has become related and tied to five companions so identical with it that only the fiction of the story permits me to distinguish them. It is a beautiful ring-shaped structure, an almost regular hexagon, which however is subjected to complicated exchanges and balances with the water in which it is dissolved; because by now it is dissolved in water, indeed in the sap of the vine, and this, to remain dissolved, is both the obligation and the privilege of all substances that are destined (I was about to say 'wish') to change. And if then anyone really wanted to find out why a ring, and why a hexagon, and why soluble in water, well, he need not worry: these are among the not many questions to which our doctrine can reply with a persuasive discourse, accessible to everyone, but out of place here.

Carl Sagan

from THE DEMON-HAUNTED WORLD

■ Carl Sagan inspired a whole generation of young scientists, especially in America, and his death from cancer in 1996 was a grievous loss to science and the whole world of reality-based thinking. Open any one of his books and you need go no further than the Table of Contents to experience the tingling of the poetic nerve endings that will continue throughout the book: The shores of the cosmic ocean...One voice in the cosmic fugue...The harmony of worlds...The backbone of night...The edge of forever...Who speaks for Earth? Carl Sagan himself would be a good candidate for the answer to the last question. Quite apart from his contributions to public understanding and appreciation of science, Sagan's own research contributions to planetary science would have been fully enough to ensure his election to the National Academy of Sciences, and it is widely believed that envy at his massive success in communicating science to the millions was the direct cause of his being blackballed for election to the Academy. Parallel to his poetic evocations of the universe, Sagan was also an influential voice against superstition and paranormal mumbo jumbo of all kinds. Debunking is often thought to be a killjoy activity: unsexy, necessary but poor box-office. I have never understood this attitude although I have often encountered it. Carl Sagan eloquently belies it in his marvellous book *The Demon-Haunted World* from which the following excerpt is taken. ■

[Science] is more than a body of knowledge; it is a way of thinking. I have a foreboding of an America in my children's or grandchildren's time—when the United States is a service and information economy; when nearly all the key manufacturing industries have slipped away to other countries; when awesome technological powers are in the hands of a very few, and no one representing the public interest can even grasp the issues; when the people have lost the ability to set their own agendas or knowledgeably question those in authority; when, clutching our crystals and nervously consulting our horoscopes, our critical faculties in decline, unable to distinguish between what feels good and what's true, we slide, almost without noticing, back into superstition and darkness. The dumbing down of America is most evident in the slow decay of substantive content in the enormously influential media, the 30-second sound bites (now down to 10 seconds or less), lowest common denominator programming, credulous presentations on pseudoscience and superstition, but especially a kind of celebration of ignorance.

[...]

We've arranged a global civilization in which most crucial elements—transportation, communications, and all other industries; agriculture, medicine, education, entertainment, protecting the environment; and even the key democratic institution of voting—profoundly depend on science and technology. We have also arranged things so that almost no one understands science and technology. This is a prescription for disaster. We might get away with it for a while, but sooner or later this combustible mixture of ignorance and power is going to blow up in our faces.

A Candle in the Dark is the title of a courageous, largely Biblically based, book by Thomas Ady, published in London in 1656, attacking the witch-hunts then in progress as a scam 'to delude the people'. Any illness or storm, anything out of the ordinary, was popularly attributed to witchcraft. Witches must exist, Ady quoted the 'witchmongers' as arguing, 'else how should these things be, or come to pass?' For much of our history, we were so fearful of the outside world, with its unpredictable dangers, that we gladly embraced anything that promised to soften or explain away the terror. Science is an attempt, largely successful, to understand the world, to get a grip on things, to get hold of ourselves, to steer a safe course. Microbiology and meteorology now explain what only a few centuries ago was considered sufficient cause to burn women to death.

Ady also warned of the danger that 'the Nations [will] perish for lack of knowledge'. Avoidable human misery is more often caused not so much by stupidity as by ignorance, particularly our ignorance about ourselves. I worry that, especially as the millennium edges nearer, pseudoscience and superstition will seem year by year more tempting, the siren song of unreason more sonorous and attractive. Where have we heard it before? Whenever our ethnic or national prejudices are aroused, in times of scarcity, during challenges to national self-esteem or nerve, when we agonize about our diminished cosmic place and purpose, or when fanaticism is bubbling up around us—then, habits of thought familiar from ages past reach for the controls.

The candle flame gutters. Its little pool of light trembles. Darkness gathers. The demons begin to stir.

There is much that science doesn't understand, many mysteries still to be resolved. In a Universe tens of billions of light years across and some ten or fifteen billion years old, this may be the case forever. We are constantly stumbling on surprises. Yet some New Age and religious writers assert that scientists believe that 'what they find is all there is'. Scientists may reject mystic revelations for which there is no evidence except somebody's say-so, but they hardly believe their knowledge of Nature to be complete.

Science is far from a perfect instrument of knowledge. It's just the best we have. In this respect, as in many others, it's like democracy. Science by itself cannot advocate courses of human action, but it can certainly illuminate the possible consequences of alternative courses of action.

The scientific way of thinking is at once imaginative and disciplined. This is central to its success. Science invites us to let the facts in, even when they don't conform to our preconceptions. It counsels us to carry alternative hypotheses in our heads and see which best fit the facts. It urges on us a delicate balance between no-holds-barred openness to new ideas, however heretical, and the most rigorous sceptical scrutiny of everything—new ideas and established wisdom. This kind of thinking is also an essential tool for a democracy in an age of change.

One of the reasons for its success is that science has built-in, error-correcting machinery at its very heart. Some may consider this an over-broad characterization, but to me every time we exercise self-criticism, every time we test our ideas against the outside world, we are doing science. When we are self-indulgent and uncritical, when we confuse hopes and facts, we slide into pseudoscience and superstition.

Every time a scientific paper presents a bit of data, it's accompanied by an error bar—a quiet but insistent reminder that no knowledge is complete or perfect. It's a calibration of how much we trust what we think we know. If the error bars are small, the accuracy of our empirical knowledge is high; if the error bars are large, then so is the uncertainty in our knowledge. Except in pure mathematics nothing is known for certain (although much is certainly false).

Moreover, scientists are usually careful to characterize the veridical status of their attempts to understand the world—ranging from conjectures and hypotheses, which are highly tentative, all the way up to laws of Nature which are repeatedly and systematically confirmed through many interrogations of how the world works. But even laws of Nature are not absolutely certain. There may be new circumstances never before examined—inside black holes, say, or within the electron, or close to the speed of light—where even our vaunted laws of Nature break down and, however valid they may be in ordinary circumstances, need correction.

Humans may crave absolute certainty; they may aspire to it; they may pretend, as partisans of certain religions do, to have attained it. But the history of science—by far the most successful claim to knowledge accessible to humans—teaches that the most we can hope for is successive improvement in our understanding, learning from our mistakes, an asymptotic approach to the Universe, but with the proviso that absolute certainty will always elude us.

We will always be mired in error. The most each generation can hope for is to reduce the error bars a little, and to add to the body of data to which error bars apply. The error bar is a pervasive, visible self-assessment of the reliability of our knowledge. You often see error bars in public opinion polls ('an uncertainty of plus or minus three per cent', say). Imagine a society in which every speech in the *Congressional Record*, every television commercial, every sermon had an accompanying error bar or its equivalent.

One of the great commandments of science is, 'Mistrust arguments from authority'. (Scientists, being primates, and thus given to dominance hierarchies, of course do not always follow this commandment.) Too many such arguments have proved too painfully wrong. Authorities must prove their contentions like everybody else. This independence of science, its occasional unwillingness to accept conventional wisdom, makes it dangerous to doctrines less self-critical, or with pretensions to certitude.

Because science carries us toward an understanding of how the world is, rather than how we would wish it to be, its findings may not in all cases be immediately comprehensible or satisfying. It may take a little work to restructure our mindsets. Some of science is very simple. When it gets complicated, that's usually because the world is complicated—or because *we're* complicated. When we shy away from it because it seems too difficult (or because we've been taught so poorly), we surrender the ability to take charge of our future. We are disenfranchised. Our self-confidence erodes.

But when we pass beyond the barrier, when the findings and methods of science get through to us, when we understand and put this knowledge to use, many feel deep satisfaction. This is true for everyone, but especially for children—born with a zest for knowledge, aware that they must live in a future moulded by science, but so often convinced in their adolescence that science is not for them. I know personally, both from having science explained to me and from my attempts to explain it to others, how gratifying it is when we get it, when obscure terms suddenly take on meaning, when we grasp what all the fuss is about, when deep wonders are revealed.

In its encounter with Nature, science invariably elicits a sense of reverence and awe. The very act of understanding is a celebration of joining, merging, even if on a very modest scale, with the magnificence of the Cosmos. And the cumulative worldwide build-up of knowledge over time converts science into something only a little short of a transnational, trans-generational meta-mind.

'Spirit' comes from the Latin word 'to breathe'. What we breathe is air, which is certainly matter, however thin. Despite usage to the contrary, there is no necessary implication in the word 'spiritual' that we are talking of anything other than matter (including the matter of which the brain is made), or anything outside the realm of science. On occasion, I will feel free to use the word. Science is not only compatible with spirituality; it is a profound source of spirituality. When we recognize our place in an immensity of light years and in the passage of ages, when we grasp the intricacy, beauty and subtlety of life, then that soaring feeling, that sense of elation and humility combined, is surely spiritual. So are our emotions in the presence of great art or music or literature, or of acts of exemplary selfless courage such as those of Mohandas Gandhi or Martin Luther King Jr. The notion that science and spirituality are somehow mutually exclusive does a disservice to both.

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ALL DAY the snow had been falling. Snow muffled every store and church; drifts erased streets and sidewalks. The punks at the new Harvard Square T stop had tramped off, bright as winter cardinals with their purple tufted hair and orange Mohawks. The sober Vietnam vet on Mass Ave had retreated to Au Bon Pain for coffee. Harvard Yard was quiet with snow. The undergraduates camping there for Harvard's divestment from South Africa had packed up their cardboard boxes, tents, and sleeping bags and begun building snow people. Cambridge schools were closed, but the Philpott Institute was open as usual. In the Mendelssohn-Glass lab, four postdocs and a couple of lab techs were working.

Two to a bench, like cooks crammed into a restaurant kitchen, the postdocs were extracting DNA in solution, examining cells, washing cells with chemicals, bursting cells open, changing cells forever by inserting new genetic material. They were operating sinks with foot pedals, measuring and moving solutions milliliter by milliliter with pipettes, their exacting eyedroppers. They were preparing liquids, ices, gels.

There was scarcely an inch of counter space. Lab benches were covered with ruled notebooks and plastic trays, some blue, some green, some red, each holding dozens of test tubes. Glass beakers stood above on shelves, each beaker filled with red medium for growing cells. The glass beakers were foil topped, like milk bottles sealed for home delivery. Peeling walls and undercounter incubators were covered with postcards, yellowing Doonesbury cartoons, photographs from a long-ago lab picnic at Walden Pond. The laminar flow hood was shared, as was the good microscope. In 1985, the Philpott was famous, but it was full of old instruments. Dials and needle indicators looked like stereo components from the early sixties. The centrifuge, designed for spinning down cells in solution, was clunky as an ancient washing machine. There wasn't enough money to buy new equipment. There was scarcely enough to pay the postdocs.

On ordinary days, the researchers darted into and out of the lab to the common areas on the floor. The cold room, warm room, and stockroom were shared with the other third-floor labs, as was the small conference room with its cheap chrome and wood-grain furniture, good for meetings and naps. But this Friday no one left the lab, not even the lab techs, Aidan and Natalya. Gofers and factotums for the postdocs, these two belonged to a scientific service class, but no one dared treat them like servants. They were strong-willed and politically aware, attuned to every power struggle. They kept darting looks at each other, as if to say "It's time to go downstairs," but they delayed going to the animal facility for fear of missing something. The lab directors, Marion Mendelssohn and Sandy Glass, were meeting in the office down the hall. They had been conferring for half an hour, and this did not bode well. One of the postdocs was in trouble.

How bad was it? No one spoke. Prithwish kept his head down over a tray of plastic tubes, eyes almost level with the avocado plant he'd grown from seed. "My most successful experiment," he often said ruefully. Robin ducked out to look up and down the hall, then brushed past Feng as she

• 11 May 1905

Walking on the Marktgasse, one sees a wondrous sight. The cherries in the fruit stalls sit aligned in rows, the hats in the millinery shop are neatly stacked, the flowers on the balconies are arranged in perfect symmetries, no crumbs lie on the bakery floor, no milk is spilled on the cobblestones of the buttery. No thing is out of place.

When a gay party leaves a restaurant, the tables are more tidy than before. When a wind blows gently through the street, the street is swept clean, the dirt and dust transported to the

edge of town. When waves of water splash against the shore, the shore rebuilds itself. When leaves fall from the trees, the leaves line up like birds in V-formation. When clouds form faces, the faces stay. When a pipe lets smoke into a room, the soot drifts toward a corner of the room, leaving clear air. Painted balconies exposed to wind and rain become brighter in time. The sound of thunder makes a broken vase reform itself, makes the fractured shards leap up to the precise positions where they fit and bind. The fragrant odor of a passing cinnamon cart intensifies, not dissipates, with time.

Do these happenings seem strange?

In this world, the passage of time brings increasing order. Order is the law of nature, the universal trend, the cosmic direction. If time is an arrow, that arrow points toward order. The future is pattern, organization, union, intensification; the past, randomness, confusion, disintegration, dissipation.

Philosophers have argued that without a trend toward order, time would lack meaning. The future would be indistinguishable from the past. Sequences of events would be just so many random scenes from a thousand novels. History would be indistinct, like the mist slowly gathered by treetops in evening.

In such a world, people with untidy houses lie in their beds and wait for the forces of nature to jostle the dust from their windowsills and straighten the shoes in their closets. People with untidy affairs may picnic while their calendars become organized, their appointments arranged, their accounts balanced. Lipsticks and brushes and letters may be tossed into purses with the satisfaction that they will sort themselves out automatically. Gardens need never be pruned, weeds never uprooted. Desks become neat by the end of the day. Clothes on the floor in the evening lie on chairs in the morning. Missing socks reappear.

If one visits a city in spring, one sees another wondrous sight. For in springtime the populace become sick of the order in their lives. In spring, people furiously lay waste to their houses. They sweep in dirt, smash chairs, break windows. On Aarbergergasse, or any residential avenue in spring, one hears the sounds of broken glass, shouting, howling, laughter. In spring, people meet at unarranged times, burn their appointment books, throw away their watches, drink through the night. This hysterical abandon continues until summer, when people regain their senses and return to order.

• 14 May 1905

There is a place where time stands still. Raindrops hang motionless in air. Pendulums of clocks float mid-swing. Dogs raise their muzzles in silent howls. Pedestrians are frozen on the dusty streets, their legs cocked as if held by strings. The aromas of dates, mangoes, coriander, cumin are suspended in space.

As a traveler approaches this place from any direction, he moves more and more slowly. His heartbeats grow farther apart, his breathing slackens, his temperature drops, his thoughts diminish, until he reaches dead center and stops. For this is the center of time. From this place, time travels outward in concentric circles—at rest at the center, slowly picking up speed at greater diameters.

Who would make pilgrimage to the center of time? Parents with children, and lovers.

And so, at the place where time stands still, one sees parents clutching their children, in a frozen embrace that will never let go. The beautiful young daughter with blue eyes and blond hair will never stop smiling the smile she smiles now, will never lose this soft pink glow on her cheeks, will never grow wrinkled or tired, will never get injured, will never unlearn what her parents have taught her, will never think thoughts that her parents don't know, will never know evil, will never tell her parents that she does not love them, will never leave her room with the view of the ocean, will never stop touching her parents as she does now.

And at the place where time stands still, one sees lovers kissing in the shadows of buildings, in a frozen embrace that will never let go. The loved one will never take his arms from where they are now, will never give back the bracelet of memories, will never journey far from his lover, will never place himself in danger in self-sacrifice, will never fail to show his love, will never become jealous, will never fall in love with someone else, will never lose the passion of this instant in time.

One must consider that these statues are illuminated by only the most feeble red light, for light is diminished almost to nothing at the center of time, its vibrations slowed to echoes in vast canyons, its intensity reduced to the faint glow of fireflies.

Those not quite at dead center do indeed move, but at the pace of glaciers. A brush of the hair might take a year, a kiss might take a thousand. While a smile is returned, seasons pass in the outer world. While a child is hugged, bridges rise. While a goodbye is said, cities crumble and are forgotten.

And those who return to the outer world . . . Children grow rapidly, forget the centuries-long embrace from their parents, which to them lasted but seconds. Children become adults, live far from their parents, live in their own houses, learn ways of their own, suffer pain, grow old. Children curse their parents for trying to hold them forever, curse time for their own wrinkled skin and hoarse voices. These now old children also want to stop time, but at another time. They want to freeze their own children at the center of time.

Lovers who return find their friends are long gone. After all, lifetimes have passed. They move in a world they do not recognize. Lovers who return still embrace in the shadows of buildings, but now their embraces seem empty and alone. Soon they forget the centuries-long promises, which to them lasted only seconds. They become jealous even among strangers, say hateful things to each other, lose passion, drift apart, grow old and alone in a world they do not know.

Some say it is best not to go near the center of time. Life is a vessel of sadness, but it is noble to live life, and without time there is no life. Others disagree. They would rather have an eternity of contentment, even if that eternity were fixed and frozen, like a butterfly mounted in a case.

• 15 MAY 1905

Imagine a world in which there is no time. Only images.

A child at the seashore, spellbound by her first glimpse of the ocean. A woman standing on a balcony at dawn, her hair down, her loose sleeping silks, her bare feet, her lips. The curved arch of the arcade near the Zähringer Fountain on Kramgasse, sandstone and iron. A man sitting in the quiet of his study, holding the photograph of a woman, a pained look on his face. An osprey framed in the sky, its wings outstretched, the sun rays piercing between feathers. A young boy sitting in

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When Black Holes Collide

Somewhere in the universe two black holes collide—as heavy as stars, as small as cities, literally black (the complete absence of light) holes (empty hollows). Tethered by gravity, in their final seconds together the black holes course through thousands of revolutions about their eventual point of contact, churning up space and time until they crash and merge into one bigger black hole, an event more powerful than any since the origin of the universe, outputting more than a trillion times the power of a billion Suns. The black holes collide in complete darkness. None of the energy exploding from the collision comes out as light. No telescope will ever see the event.

That profusion of energy emanates from the coalescing holes in a purely gravitational form, as waves in the shape of spacetime, as gravitational waves. An astronaut floating nearby would see nothing. But the space she occupied would ring, deforming her, squeezing then stretching. If close enough, her auditory mechanism could vibrate in response. She would *hear* the wave. In empty darkness, she could hear spacetime ring. (Barring death by black hole.) Gravitational waves are like sounds without a material medium. When black holes collide, they make a sound.

No human has ever heard the sound of a gravitational wave. No instrument has indisputably recorded one. Traveling from the impact as fast as light to the Earth could take a billion years, and by the time the gravitational wave gets from the black hole collision to this planet, the din of the crash is imperceptibly faint. Fainter than that. Quieter than can be described with conventional superlatives. By the time the gravitational wave gets here, the ringing of space will involve relative changes in distance the width of an atomic nucleus over a stretch comparable to the span of three Earths.

A campaign to record the skies began a half century ago. The Laser Interferometer Gravitational-Wave Observatory (LIGO) is to date the most expensive undertaking ever funded by the National Science Foundation (NSF), an independent federal agency that supports fundamental scientific research. There are two LIGO observatories, one in Hanford, Washington, and the other in Livingston, Louisiana. Each machine frames 4 square kilometers. With integrated costs exceeding a billion dollars and an international collaboration of hundreds of scientists and engineers, LIGO is the culmination of entire careers and decades of technological innovation.

The machines were taken offline over the past few years for an upgrade to their advanced detection capabilities. Everything was replaced but the nothing—the vacuum—one of the experimentalists told me. In the meantime, calculations and computations are under way in groups across the world to leverage predictions of the universe at its noisiest. Theorists take the intervening years to design data algorithms, to build data banks, to devise methods to extract the most from the instruments. Many scientists have invested their lives in the experimental goal to measure “a change in distance comparable to less than a human hair relative to 100 billion times the circumference of the world.”

In the hopefully plentiful years that follow a first detection, the aspiration is for Earth-based observatories to record the sounds of cataclysmic astronomical events from many directions and from varied distances. Dead stars collide and old stars explode and the big bang happened. All kinds of high-impact mayhem can ring spacetime. Over the lifetime of the observatories, scientists will reconstruct a clanging discordant score to accompany the silent movie humanity has compiled of the history of the universe from still images of the sky, a series of frozen snapshots captured over the past four hundred years since Galileo first pointed a crude telescope at the Sun.

I follow this monumental experimental attempt to measure subtle shifts in the shape of spacetime in part as a scientist hoping to make a contribution to a monolithic field, in part as a neophyte hoping to understand an unfamiliar machine, in part as a writer hoping to document the first human-procured records of bare black holes. As the global network of gravity observatories nears the final stretch of this race, it gets harder to turn attention away from the promise of discovery, although there are still those who vehemently doubt the prospects for success.

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Under the gloom of a controversial beginning and the opposition of powerful scientists, grievous internal battles, and arduous technological dilemmas, LIGO recovered and grew, hitting projections and escalating in capability. Five decades after the experimental ambition began, we are on the eve of the crash of a colossal machine into a wisp of a sound. An idea sparked in the 1960s, a thought experiment, an amusing haiku, is now a thing of metal and glass. Advanced LIGO began to record the skies in the fall 2015, a century after Einstein published his mathematical description of gravitational waves. The instruments should reach optimum sensitivity within a year or two, maybe three. The early generation of machines proved the concept, but still success is never guaranteed. Nature doesn’t always comply. The advanced machines will lock on and tolerate adjustments and corrections and calibrations and wait for something extraordinary to happen, while the scientists push aside their doubts and press toward the finish.

As much as this book is a chronicle of gravitational waves —a sonic record of the history of the universe, a soundtrack to match the silent movie—it is a tribute to a quixotic, epic, harrowing experimental endeavor, a tribute to a fool’s ambition.

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High Fidelity

At 6:00 PM the building is quiet for an MIT headquarters. I have to wait outside until a graduate student rolls up and pops off a bicycle to let me in the locked doors, carrying the bike with her up the stairs. “Rai’s office is straight down.” She points to the hall behind her and wheels away, one foot jumped into the stirrup of the pedal, the other hanging on the same side. She hops off again and is inhaled by a pale office door. Rai’s door looks exactly the same and I have the sense it would be easy to mistake offices, like mistaking hotel rooms.

Rainer Weiss waves me in. We skip conventional social openers and speak with familiarity, although this is our first meeting, as though we’ve known each other for as long as imaginable, the shared experience of our scientific community outweighing a shared hometown or even generation. We lean back in mismatched chairs, our feet propped up on a single stool.

“I started life with one ambition. I wanted to make music easier to hear. As a kid I was in the revolution of high fidelity. Because, look, I was a kid in around 1947. I built hi-fis of the first kind. The immigrants that came to New York, most of them were very eager to listen to classical music.

“See that loudspeaker there? That came from a movie theater in Brooklyn. Behind the screen you had a matrix of those things. I had twenty of them. I lugged them all on the subway. They had a huge fire at the Brooklyn Paramount, and they were getting rid of them. So I had what were movie-studio quality loudspeakers and I had this fantastic circuit that I was building and I had FM radio. And I would invite friends over to listen to the New York Philharmonic and it was unbelievable. You felt like you were in the theater. An unbelievable sound came out of those things.”

Rai gestures to the conical metal guts of a circa 1935 speaker. The raw frame has an exaggerated heft that design advances have banished but otherwise looks surprisingly technologically recent, more 1970s indulgence than 1930s necessity. The object fits in visually with the other metal frames from various apparatuses that are stashed around the hive of scientists attending to a gravitational instrument that first imposed itself as a compelling thought experiment in the 1960s. Although he would later find out he wasn’t the first, Rai dreamed up a device to record the sound of spacetime ringing. A paragon of scientific ambition, the experiment is now too colossal for this building or even for Cambridge, Massachusetts. An R&D laboratory to develop some of the machines’ components is housed in the basement of the building next door, while the fully integrated instruments are constructed on remote sites.

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Beginnings and Ends

A COLD WIND BLOWING IN FROM LONG ISLAND SOUND WHISPERED THROUGH the cranes and scaffolding over our heads. It was just after dawn. Snow had fallen a few days before, melted, and refrozen into glassy ovals now glittering with first light. Twenty feet from where we stood, a dozen men surrounded a metal object that resembled a giant wedding band, silver in color and fifty feet in diameter. The men wore hardhats and gloves and heavy boots; some had toolkits on their belts. Steam drifted from their lips and coffee mugs. Despite the cold, they were working carefully, even slowly. Inside the shiny band at their feet was a spool of high-precision cable lent by a laboratory in Japan and wound to a tolerance of thousandths of an inch; nobody wanted to ruin the alignment in the process of transporting it. Perhaps fifty feet away from the ring stood its destination—a metal shed. Inside its featureless gray walls, scores of physicists had spent almost ten years and millions of dollars in government funds to penetrate deeper into the heart of matter than humankind had ever been before.

A particle physicist named Gerry Bunce was meeting us at the site. Rangy and affable, he greeted us with casual, unprintable reflections on the state of the weather, the practice of rising before dawn, and the wisdom of locating a laboratory on a flat island with no nearby ski facilities. The bleakness of the day was appropriate, for the landscape that surrounded us was a trashed technological wonderland: great cylindrical gas tanks; pipes, ladders, and girders of

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The Man Who Talked

ON A GRAY RAINY STREET IN THE CENTER OF THE GRAY RAINY CITY OF Copenhagen is a small cluster of buildings that protrudes into the side of a city park. Neatly tended and vaguely inhospitable in the Continental manner, Faelled Park is a stretch of wet greensward laced by gravel paths that run beneath stands of trees. The park is old, square, pristine, proudly aloof from city life—except where the complex on its edge has gobbled up a meadow and nibbled at the edges of a gathering of oak. As if to disguise their intrusion, the buildings cut into the flank of Faelled Park have inconspicuous slate-colored walls and red tile roofs and curtained windows like their neighbors in Copenhagen proper. They are, however, one of Europe's greatest centers of theoretical physics and a living monument to the torchbearer of the quantum revolution, Niels Hendrik David Bohr.

Bohr's working habits have become legendary among his successors, part of the lore of science along with Einstein's flyaway hair and Rutherford's remark that relativity was not meant to be understood by Anglo-Saxons. Bohr *talked.* He discovered his ideas in the act of enunciating them, shaping thoughts as they came out of his mouth. Friends, colleagues, graduate students, all had Bohr gently entice them into long walks in the countryside around Copenhagen, the heavy clouds scudding overhead as Bohr thrust his hands into his overcoat pockets and settled into an endless, hesitant, recondite, barely audible monologue. While he spoke, he

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A Children's Crusade

"PEOPLE, " HOWARD GEORGI SAID, "STILL HAVE AN EINSTEIN COMPLEX." WE were sitting in his office in Lyman Hall, a lumpy pile of brick in an unlovely corner of the Harvard University campus that over the last thirty years has hosted many of the brightest luminaries in theoretical physics, Georgi among them. His window was open, and the sound of construction drifted across the small, paper-strewn room. Georgi is a tall, limber man with a wide face and an even wider russet beard curled around the edges of his smile. That morning he was wearing tennis shorts and sneakers; his white socks were pulled up nearly to his knees. He was talking about his generation of physicists, the successors to Werner Heisenberg, Bohr, and Planck, and explaining a dissatisfaction, common among his colleagues, with certain aspects of the public legacy of Albert Einstein. As he spoke, he gestured toward a small picture of the savant thumbtacked to a bulletin board. Rumpled, sorrowful, and ethereal, Einstein looked as if he were ready to sink beneath the weight of his own wisdom, whereas Georgi was the picture of American health—he had just come off a tennis court. A racket in its press lay across the papers on his desk. Yellow-green tennis balls dotted the floor, a menace to visitors. "Revolution!" Georgi said, dismissing the subject. "You're always getting asked if physics is having another revolution, if it's like Einstein all over again. But that's not the point at all. The things we've learned are so *interesting*—" here a quick burst of his infectious, high-pitched laughter "—that it's just

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Uncertainty's Triumph

ONE OF THE MOST TRYING ASPECTS OF PRACTICING THE ART OF PHYSICS IS that the shape of the answer is not known from the outset. Although they can draw upon advanced experimental technology and the wealth of data collected by past scientists, physicists must work in the dark whenever they proceed close to the frontier of knowledge; they are aided only by a set of aesthetic prejudices, a few mathematical tools, and the knowledge that whatever they come across is unlikely to contradict directly the conclusions of the past, although it may modify them. The ideas of theoreticians must be at least somewhat amenable to being tested by others in the community; experimenters need to make it seem plausible that others could reproduce their work, and achieve the same results. But these guidelines leave more than enough room for error, and the scientists who make the most remarkable advances—perhaps especially the most remarkable advances—are almost inevitably haunted by doubt, anxiety, and the fear of being forgotten.

Consider Werner Heisenberg, residing temporarily at Göttingen, writing to his close friend, Wolfgang Pauli, on the very day that the three-man paper on matrix mechanics is received by the office of the *Zeitschrift für Physik*. Heisenberg encloses a copy, now apparently lost, of the typescript, which, like most products of Göttingen at the time, is laced with complex

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The Man Who Listened

THE STANDARD MODEL OF ELEMENTARY PARTICLE INTERACTIONS WAS pieced together by three distinct intellectual generations of twentieth-century physicists. Each arrived suddenly, of a piece, in the course of two or three years, a group of young men—women as well, in the case of the third—which emerged with their style of play fully developed, in confident command of the tools of the trade. Like the abstract expressionists, whose intemperate urgency and immediate prominence in postwar New York City stunned their elders, the new physicists startled their contemporaries with the sweep and precision of their attack and the fierceness with which they demanded to be heard. Although, like the expressionist Willem de Kooning, the new workers may actually have labored unrecognized for years, it seems to the community at large that a movement has abruptly formed, fast and bright as a stroke of lightning, and that everything has changed. The construction of quantum mechanics, in the mid-1920s, was the work of the first *nouvelle vague*; names like Heisenberg, Pauli, and Oppenheimer, Rabi, Schrödinger, and Jordan, suddenly appeared on papers that had to be read by every serious practitioner in the field. Meanwhile, the old hands, the Rutherfords and Bohrs, were pushed to new accomplishments. (Some never adjusted; J. J. Thomson was one, and—sadly, grandly—Einstein was another.) The years immediately after the Second World War marked the entrance of another group of scientists—young, hungry,

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Infinity

WOLFGANG PAULI READ THE FIRST OF DIRAC S TWO PAPERS ON THE ELECtron with characteristic care as soon as the *Proceedings of the Royal Society* came in the mail. Pauli understood immediately that an equation for a single electron floating through space could be nothing more than a starting point, for most situations in the real world involve many electrons interacting with each other; he seems also to have realized that the constant presence of virtual particles in the subatomic domain made the very idea of talking about one particle by itself unrealistic—unphysical, in the scientist's phrase. Pauli promptly dispatched a letter to Dirac informing him of the necessity to formulate quantum electrodynamics without such a dubious assumption. In the middle of a discourse on the version of quantum electrodynamics that he and Heisenberg were working on, Pauli broke off to ask, "I would like to ask your opinion about what is essentially a physical difficulty that Heisenberg and I have run into and can't get around." It seemed that their calculations were being thrown off whenever "the problem of 'a particle interacting with itself' rears its ugly head."

In certain conditions, an electron is affected by the electromagnetic field it gives off, in somewhat the way that a boat can be rocked by its own wake, or an airplane shaken by the sonic boom it has created. Working ever deeper into the thickets of quantum electrodynamics, Pauli and Heisenberg had become

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The Shift

EVERY NOW AND THEN, A FACT, A SINGLE ASPECT OF NATURE, ASSUMES AN importance to physicists far outside of its intrinsic significance, and it makes or breaks theories, careers, reputations. After the contretemps is over, the fact becomes a footnote in future papers, and the irregular means by which it was brought to light is forgotten. The next generation of physicists learns the fact in graduate school as an accepted part of the world; it seems to have appeared in experimental equipment when required, its importance never in doubt, and to have been there always—had past scientists only possessed the wit to seek it.

Such a fact is the exact energy level of the $2S_{1/2}$ ("two-ess-one-half") electron orbital in atomic hydrogen.* One of the lowest, simplest excited states of the lightest and simplest atom, its location is a corollary of quantum theory. The study of this orbital was the subject of a dozen experiments during the 1930s, all of which bore directly on the worth of quantum field theory in general and the renormalizability of quantum electrodynamics in particular. But, because science is a human enterprise of fallible people, ideas were not put together, connections short-circuited, and the result was a slow tragicomedy on the experimental side that accompanied the contortions of the theoreticians. While theorists spent the 1930s alternating between pretending the infinities weren't there and fruitlessly trying to grapple with them, experimenters passed the same decade painfully trying to decide if

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Symmetry

AT HALF PAST FOUR IN THE AFTERNOON OF DECEMBER 10, 1979, THREE men—Sheldon Glashow, Abdus Salam, and Steven Weinberg—entered the auditorium of the Stockholm Concert Hall to a flourish of trumpets. They were to be awarded the Nobel Prize for physics, for their construction of a single theory incorporating weak and electromagnetic interactions, an achievement that began, almost unnoticed, in the years following the discovery of the strange particles. The laureates walked down the wide aisle— Glashow and Weinberg in tails and studs; Salam in full Pakistani formal regalia, including shoes with toes that curled several painful inches into the air—and onto a platform, where they were introduced and individually extolled by a middle-aged member of the Swedish Academy of Sciences. At the end of each peroration, the two thousand people in the audience applauded as the prizewinner walked to center stage to meet King Gustav XVI, who presided over the ceremony. Each physicist shook the king's hand and received a leather-bound diploma, a hefty gold medal, and a letter informing him of when and how to collect his share of the prize money.[1]

After the rite, the three physicists, the laureates in chemistry, medicine, literature, and economics, the royal family, and about half the people in the concert house were bundled into a fleet of chartered limousines and buses that conducted them through the bitter cold to Stockholm City Hall. (The Peace Prize is awarded in

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The King and His Quarks

THROUGHOUT THE LAST CENTURY *QUARK* WAS A RARE, POETIC TERM FOR A particular type of animal call, the cry of a heron or gull. Nobody is ever likely to use the word in this sense again, for during the past two decades it made an abrupt transition in meaning from bird caw to subatomic particle fragment, surely one of the most bizarre etymological twists in the history of language. This movement began in 1939 with the publication of James Joyce's last novel, *Finnegans Wake*. Its hero is a Dublin pub owner named, variously, H. C. Earwicker, Here Comes Everybody, and even "Heinz cans everywhere." He is asleep throughout the book; his dreams, which are recounted in its pages, are the expressions of a collective unconscious, reenacting myths, historical incidents, and even the rise and fall of civilizations. As befits a dream, however, the events and scenes of the book do not unfold with the sequential logic of a television miniseries, but through a dense collage of puns, repetitions, misspellings (which begin with the deliberate omission of an apostrophe from the work's title), allusions, and other linguistic highjinks.

The fourth episode in the second section of *Finnegans Wake* begins with the hoots and babbles of four old men, who represent the four authors of the Gospels, the four ancient historians of Ireland, and anything else that comes in fours, as they chortle over the old Celtic romance of Tristan, a young nobleman, and Iseult, the wife of Tristan's uncle Mark, King of

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Neutral Currents/Alternating Currents

IT IS IMPOSSIBLE TO LEARN ABOUT SCIENCE—OR ANYTHING ELSE, FOR THAT matter—without asking a lot of stupid questions. Every scientist has a humiliating memory of revealing ignorance by posing a particularly naïve question to a teacher or a senior colleague. Etched into the brain, the sarcastic response is savored, years later, for the lesson it imparted; being caught short may not be the most comfortable way to learn, but one seldom forgets the result.

While poring over the epochal alpha particle experiment by which Ernest Rutherford divined the existence of the nucleus, we had the notion that we would better understand the discovery if we repeated the experiment with a practicing scientist. We had an enticing image of ourselves watching as the physicist set up the radioactive source, the thin gold foil, and the scintillation screens. We envisioned scribbling notes blindly as the lights were turned out and the little telescope adjusted to count the flashes at each angle. Making a few quick calculations on a scrap of paper, our physicist would announce triumphantly that the evidence indicated that atoms have solid, massy, positively charged centers.

An obvious candidate for this signal honor was Samuel Devons, a former Cavendish physicist who had taught a course on the art of experiment at Barnard College in Manhattan. We broached the idea one day to him and had the embarrassing experience of hearing a kind man attempting not to laugh in our

Descriptions of Nature: Details

Letter to Alexander Chekhov, Moscow, May 19, 1886

I think that descriptions of nature should be short and to the point. Commonplaces such as, "The setting sun bathing in the waves of the darkening sea poured out a flood of crimson gold," etc., and, "The swallows skimming the surface of the water chirped joyously"—such commonplaces should be eliminated. In describing nature, focus on minute details and group them in such a way that when the reader will have finished reading, he will be able to close his eyes and see a complete picture. You can produce the impression of a moonlit night, for example, by writing that the broken bottle glass twinkled like stars on the milldam, and that the black shadow of a dog or a wolf rolled by, and so on. Nature appears to be animated if you are not afraid to use comparisons between natural phenomena and human actions.

COLLECTED FRAGMENTS

Notebook

Always keep a notebook on hand to jot down facts, observations, turns of phrase, and to record statements and interviews.

WHEN TRAVELING:

Do Not Make Too Many Plans

Sometimes it is useful to leave things up to chance, especially when in an unfamiliar setting.

Accept Invitations

Go to dinner, pay attention to the furnishings and the food, listen to the guests, and take part in the conversation.

Take Walks

Take walks with a companion or by yourself, to talk things over and try to get a detached view of things.

Join Celebrations

Observe the preparations, rites, and participants; note the atmosphere.

Make Tours of Inspection

Visit sites at times suitable for seeing how they normally function.

Listen to Rumors

Listen to gossip and check on sources to verify reliability; try to determine why false rumors receive as much credence as accurate reports.

Study the Graffiti

Ask yourself why people write on benches and walls.

Note the Signs of Social Hierarchy

Be attentive to formal and informal forms of address, hat doffing, use of space, sartorial details, and bodily marks.

Pay Attention to Place Names

Consider the significance of place or street names.

Note Traces of the Past

Ask yourself whether the appearance of buildings, house furnishings, and speech patterns might not retain traces of the past, and in what ways they might do so.

Use Your Nose

Take in smells, identify their source, describe them using plain language, and try to determine their chemical composition.

Listen

Listen to noises, sounds, and background voices.

Touch

Use your sense of touch.

Save Receipts, Schedules, and Fliers

Whenever possible, collect documents, pamphlets, and announcements.

Take a Census

When facts are unavailable, it is useful to take a census, not so much to obtain statistics, as to gain access to homes and the chance of meeting people.

Frame Questions

Do not solicit answers that already exist in written sources; formulate questions that produce clear responses;

Conversation, Not Interrogation

Have conversations with people you meet on the street, or at work, or visiting over tea.

Study Children

Talk with children and observe their games to understand, among other things, the adult world.

Tell the Story of the Journey

Relate the story of the journey from start to finish, describing the places and the events you experienced—even if these have nothing to do with your main argument—because these will help put your recollections in context.

Make Inventories

Draw up lists of objects and instruments.

Ascertain Reliability

Understand the premises and biases of the source material.

Make Comparisons

Juxtapose material from the most diverse sources, including your own experiences.

Explain Discrepancies Between Questions and Answers

Sometimes the most interesting answers can be those that are incorrect or approximate, or even not answers at all.

INSERT YOURSELF INTO THE SCENE

Reflect on What Is Happening

Keep in mind that the investigator is also the object of observation.

Share Your Emotions

When describing an episode in which you were a participant, describe the emotions you experienced.

Write as if You Were Painting

Imagine that you are painting a picture with all the details and colors.

Use Photographs

When describing a place, a situation, or a person, keep a photograph in front of you.

Report Conversations

Use direct discourse to report a conversation.

Tell Stories as They Were Told

Tell the stories that were told to you in the words of the original speakers, or try switching between their voices and yours.

Juxtapose the Past and the Present

When you give a description of a place, tell what it was like in the past and how it has changed, drawing on travelers' accounts and the reminiscences of old-time residents.