VINTAGE

KNOCKING ON HEAVEN'S DOOR

LISA RANDALL

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***Sunday Times* Science Book of the Year**

We are poised on the edge of discovery in particle physics (the study of the smallest objects we know of) and cosmology (the study of the largest), and when these breakthroughs come, they will revolutionise what we think we know about the universe, and the modern world.

Lisa Randall guides us through the latest ideas, charting the thrilling progress we have made in understanding the universe – from Galileo and Newton to Einstein and the Large Hadron Collider and the search for the Higgs boson. Yet it’s about more than just physics – Randall explains how we decide what questions to ask; how risk, beauty, creativity and truth play a role in scientific thinking; and how answering the big questions will ultimately tell us who we are and where we came from.

About the Author

Professor Lisa Randall studies theoretical particle physics and cosmology at Harvard University and is among the most cited and influential of all theoretical physicists. She has also communicated to a wider public through her writing, lectures and radio and TV appearances. Her book *Warped Passages: Unravelling the Mysteries of the Universe's Hidden Dimensions* was included in the *New York Times*'s '100 notable books of 2005'. She was featured in *Newsweek*'s 'Who's Next in 2006' and was one of *Time* magazine's '100 Most Influential People' of 2007. In 2008 Randall was one of *Esquire* magazine's '75 Most Influential People of the 21st Century' and was featured by *Rolling Stone* as an 'RS100: Agents of Change' in 2009. She is a member of the National Academy of Sciences, the American Philosophical Society and the American Academy of Arts and Sciences. Randall is also an Honorary Member of the Royal Irish Academy and an Honorary Fellow of the Institute of Physics. Her libretto for *Hypermusic Prologue: A Projective Opera in Seven Planes* premiered at the Pompidou Centre in Paris in 2009.

Also by Lisa Randall

Warped Passages: Unravelling the Universe's
Hidden Dimensions

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LISA RANDALL

Knocking on Heaven's Door

How Physics and Scientific Thinking Illuminate our Universe

VINTAGE BOOKS
London

INTRODUCTION

We are poised on the edge of discovery. The biggest and most exciting experiments in particle physics and cosmology are under way and many of the world's most talented physicists and astronomers are focused on their implications. What scientists find within the next decade could provide clues that will ultimately change our view of the fundamental makeup of matter or even of space itself—and just might provide a more comprehensive picture of the nature of reality. Those of us who are focused on these developments don't anticipate that they will be mere post-modern additions. We look forward to discoveries that might introduce a dramatically different twenty-first-century paradigm for the universe's underlying construction—altering our picture of its basic architecture based on the insights that lie in store.

September 10, 2008, marked the historic first trial run of the Large Hadron Collider (LHC). Although the name—Large Hadron Collider—is literal but uninspired, the same is not true for the science we expect it to achieve, which should prove spectacular. The "large" refers to the collider—not to hadrons. The LHC contains an enormous 26.6 kilometer[1] circular tunnel deep underground that stretches between the Jura Mountains and Lake Geneva and crosses the French-Swiss border. Electric fields inside this tunnel accelerate two beams, each consisting of billions of protons (which belong to a class of particles called hadrons—hence the collider's name), as they go around—about 11,000 times each second.

The collider houses what are in many respects the biggest and most impressive experiments ever built. The goal is to perform detailed studies of the structure of matter at distances never before measured and at energies higher than have ever been explored before. These energies should generate an array of exotic fundamental particles and reveal interactions that occurred early in the universe's evolution—roughly a trillionth of a second after the time of the Big Bang.

The design of the LHC stretched ingenuity and technology to their limits and its construction introduced even further hurdles. To the great frustration of physicists and everyone else interested in a better understanding of nature, a bad solder connection triggered an explosion a mere nine days after the LHC's auspicious initial run. But when the LHC came back on line in the fall of 2009—working better than anyone had dared anticipate—a quarter-century promise emerged as a reality.

In the spring of that same year, the Planck and Herschel satellites were launched in French Guiana. I learned about the timing from an excited group of Caltech astronomers who met May 13 at 5:30 A.M. in Pasadena, where I was visiting, to witness remotely this landmark event. The Herschel satellite will give insights into star formation, and the Planck satellite will provide details about the residual radiation from the Big Bang—yielding fresh information about the early history of our universe. Launches such as this are usually thrilling but very tense—since two to five percent fail, destroying years of work on customized scientific instruments in those satellites that fall back to Earth. Happily this particular launch went very well and sent information back throughout the day, attesting to just how successful it had been. Even so, we will have to wait several years before these satellites give us their most valuable data about stars and the universe.

* *

Physics now provides a solid core of knowledge about how the universe works over an extremely large range of distances and energies. Theoretical and experimental studies have provided scientists with a deep understanding of elements and structures, ranging from the extremely tiny to the very large. Over time, we have deduced a detailed and comprehensive story about how the pieces fit together. Theories successfully describe how the cosmos evolved from tiny constituents that formed atoms, which in turn coalesced into stars that sit in galaxies and in larger structures spread throughout our universe, and how some stars then exploded and created heavy elements that entered our galaxy and solar system and which are ultimately essential to the formation of life. Using the results from the LHC and from such satellite explorations as those mentioned above, today's physicists hope to build on this solid and extensive base to expand our understanding to smaller distances and higher energies, and to achieve greater precision than has ever been reached before. It's an adventure. We have ambitious goals.

You have probably heard very clear, apparently precise definitions of science, particularly when it is being contrasted with belief systems such as religion. However, the real story of the evolution of science is complex. Although we like to think of it—at least I did when first starting out—as a reliable reflection of external reality and the rules by which the physical world works, active research almost inevitably takes place in a state of indeterminacy where we hope we are making progress, but where we really can't yet be sure. The challenge scientists face is to persevere with promising ideas while all the time questioning them to ascertain their veracity and their implications. Scientific research inevitably involves balancing delicately on the edge of difficult and sometimes conflicting and competing—but often exciting—ideas. The goal is to expand the boundaries of knowledge. But when first juggling data, concepts, and equations, the correct interpretation can be uncertain to everyone—including those most actively involved.

My investigations focus on the theory of elementary particles (the study of the smallest objects we know of), with forays into string theory as well as cosmology—the study of the largest. My colleagues and I try to understand what's at the core of matter, what's out there in the universe, and how all the fundamental quantities and properties that experimenters discover are ultimately connected. Theoretical physicists like myself don't do the actual experiments that determine which theories apply in the real world. We try instead to predict possible outcomes for what experiments might find and help devise innovative means for testing ideas. In the foreseeable future, the questions we try to answer will likely not change what people eat for dinner each day. But these studies could ultimately tell us about who we are and where we came from.

Knocking on Heaven's Door is about our research and the most important scientific questions we face. New developments in particle physics and cosmology have the potential to revise radically our understanding of the world: its makeup, its evolution, and the fundamental forces that drive its operation. This book describes experimental research at the Large Hadron Collider and theoretical studies that try to anticipate what they will find. It also describes research in cosmology—how we go about trying to deduce the nature of the universe, and in particular that of the dark matter hidden throughout the universe.

But *Knocking on Heaven's Door* also has a wider scope. This book explores more general questions that pertain to all scientific investigations. Along with describing the frontiers of today's research, clarifying the nature of science is at the core of what this book is about. It describes how we go about deciding which are the right questions to pose, why scientists don't always agree even on that, and how correct scientific ideas ultimately prevail. This book explores the real ways in which science advances and the respects in which it contrasts with other ways of seeking truth, giving some of the philosophical underpinnings of science and describing the intermediate stages at which it is uncertain where we will end up or who is right. Also, and as importantly, it shows how scientific ideas and methods might apply outside science, thus encouraging more rational decision-making in other spheres as well.

Knocking on Heaven's Door is intended for an interested lay reader who would like to have a greater understanding of current theoretical and experimental physics and who wants a better appreciation of the nature of modern science—as well as the principles of sound scientific thought. Often people don't really understand what science is and what we can expect it to tell us. This book is my attempt to correct some of the misconceptions—and perhaps vent a little of my frustration with the way science is currently understood and applied.

The last few years have provided me with some unique experiences and with conversations that have taught me a great deal, and I want to share these as launching points to explore some important ideas. Although I'm not a specialist in all the areas I cover and there is not enough space to do them all full justice, my hope is that this book will lead readers in more productive directions, while elucidating some exciting new developments along the way. It should also help readers identify the most reliable sources of scientific information—or misinformation—when they look for further answers in the future. Some of the ideas this book presents might appear very basic, but a more thorough understanding of the reasoning that underlies modern science will help pave a better approach both to research and to important issues the modern world currently faces.

In this era of movie prequels, you can think of *Knocking on Heaven's Door* as the origin story to my previous book, *Warped Passages*, combined with an update of where we are now and what we are anticipating. It fills in the gaps—going over the basics about science that underlie new ideas and new discoveries—and explains why we're on the edge of our seats waiting for new data to emerge.

The book alternates between details of science being done today and reflections on the underlying themes and concepts that are integral to science but that are useful for understanding the broader world as well. The first part of the book, Chapters 11 and 12 in the second part, Chapters 15 and 18 in the third part, and the final (Roundup) part are more about scientific thinking, whereas the remaining chapters focus more on physics—where we are today and how we got there. In some respects, it is two books in one—but books that are best read together. Modern physics might appear to some to be too far removed from our daily lives to be relevant or even readily comprehensible, but an appreciation of the philosophical and methodological underpinnings that guide our thinking should clarify both the science and the relevance of scientific thinking—as we'll see in many examples. Conversely, one will only fully grasp the basic elements of scientific thinking with some actual science to ground the ideas. Readers with a greater taste for one or the other might choose to skim or skip one of the courses, but the two together make for a well-balanced meal.

A key refrain throughout the book will be the notion of scale. The laws of physics provide a consistent framework for how established theoretical and physical descriptions fit together into a coherent whole, from the infinitesimal lengths currently explored at the LHC to the enormous size of the entire cosmos.[2] The rubric of scale is critical to our thinking, as well as to the specific facts and ideas we will encounter. Established scientific theories apply to accessible scales. But those theories become absorbed in increasingly precise and more fundamental ones as we add newly gained knowledge from previously unexplored distances—small or large. The first chapter focuses on the defining element of scale, explaining how categorizing by length is essential to physics and to the way in which new scientific developments build upon prior ones.

The first part also presents and contrasts different ways of approaching knowledge. Ask people what they think about when they think about science, and the answers are likely to be as varied as the individuals you ask. Some will insist on rigid, immutable statements about the physical world. Others will define it as a set of principles that are constantly being replaced, and still others will respond that science is nothing more than another belief system, not qualitatively different from philosophy or religion. And they would all be wrong.

The evolving nature of science is at the heart of why there can be so much debate—even within the scientific community itself. This part presents a little of the history that informs how today’s research is rooted in seventeenth-century intellectual advances and then continues with a couple of less-featured aspects of the science-religion debate—a confrontation that in some respects originated at that time. It also looks into the materialist view of matter and its thorny implications for the science-religion question, as well as the issue of who gets to answer fundamental questions and how they go about it.

Part II turns to the physical makeup of the material world. It charts the terrain for the book's scientific journey, touring matter from familiar scales down to the smallest ones, all the while partitioning according to scale. This path will take us from recognizable territory down to submicroscopic sizes whose internal structure can be probed only by giant particle accelerators. The section closes with an introduction to some of the major experiments being performed today—the Large Hadron Collider (LHC) and astronomical probes into the early universe—which should broaden the extreme edges of our understanding.

As with any exciting development, these bold and ambitious enterprises have the potential to alter radically our scientific worldview. In Part III, we'll start to dig down into the LHC's operations and explore how this machine creates and collides proton beams to produce new particles that should tell us about the smallest accessible scales. This section also explains how experimenters will interpret what is found.

CERN (as well as the hilariously misleading Hollywood blockbuster *Angels and Demons*) has gone a long way toward publicizing the experimental side of particle physics. Many have now heard of the giant particle accelerator that will smash together very energetic protons that will be focused in a tiny region of space to create forms of matter never seen before. The LHC is now running and is poised to change our view of the fundamental nature of matter and even of space itself. But we don't yet know what it will find.

In the course of our scientific journey, we'll reflect on scientific uncertainty and what measurements can truly tell us. Research is by its nature at the edge of what we know. Experiment and calculation are designed to reduce or eliminate as many uncertainties as possible and precisely determine those that remain. Nonetheless, though it might sound paradoxical, in practice, on a day-to-day basis, science is fraught with uncertainty. Part III examines how scientists address the challenges intrinsic to their difficult explorations and how everyone can benefit from scientific thinking when interpreting and understanding statements that are made in an increasingly complex world.

Part III also considers black holes at the LHC, and how the fears that were raised about them contrast with some real dangers we currently face. We'll consider the important issues of cost-benefit analysis and risk, and how people might better approach thinking about them—both in and out of the lab.

Part IV describes the Higgs boson search as well as specific models, which are educated guesses for what exists and are search targets for the LHC. If LHC experiments confirm some of the ideas theorists have proposed—or even if they uncover something unforeseen—the results will change the way we think about the world. This section explains the Higgs mechanism responsible for elementary particle masses as well as the hierarchy problem that tells us we should find more. It also investigates models that address this problem and the exotic new particles they predict, such as those associated with supersymmetry or extra dimensions of space.

Along with presenting specific hypotheses, this part explains how physicists go about constructing models and the efficacy of guiding principles such as "truth through beauty" and "top-down" versus "bottom-up." It explains what the LHC is searching for, but also how physicists anticipate what it might find. This part describes how scientists will try to connect the seemingly abstract data the LHC will produce to some of the deep and fundamental ideas that we currently investigate.

Following our tour of research into the interior of matter, we'll look outward in Part V. At the same time as the LHC probes the tiniest scales of matter, satellites and telescopes explore the largest scales in the cosmos—studying the rate at which its expansion accelerates—and also study details of the relic radiation from the time of the Big Bang. This era could witness astounding new developments in *cosmology*, the science of how the universe evolved. In this section, we'll explore the universe out to larger scales and discuss the particle physics–cosmology connection, as well as the elusive dark matter and experimental searches for it.

The final roundup in Part VI reflects on creativity, and the rich and varied elements of thought that enter into creative thinking. It examines how we attempt to answer the big questions through the somewhat smaller seeming activities we engage in on a day-to-day basis. We'll conclude with some final thoughts on why science and scientific thinking are so important today, as well as the symbiotic relationship between technology and scientific thinking that has produced so much progress in the modern world.

I am frequently reminded how tricky it can be for non-scientists to appreciate the sometimes remote ideas that modern science addresses. This challenge became apparent when I met with a class of college students following a public lecture I gave about extra dimensions and physics. When I was told they all had the same pressing question, I expected some confusion about dimensions, but instead learned that they were eager to know my age. But lack of interest isn't the only challenge—and the students actually did go on to engage with the scientific ideas. Still, there is no denying that fundamental science is often abstract, and justifying it can be difficult—a hurdle I had to face at a congressional hearing about the importance of basic science that I attended in the fall of 2009 along with Dennis Kovar, director of High Energy Physics at the U.S. Department of Energy; Pier Oddone, director of the Fermi National Accelerator Laboratory; and

Hugh Montgomery, director of Jefferson Lab, a nuclear physics facility. This was my first time in the halls of government since my congressman, Benjamin Rosenthal, took me around when I was a high school finalist in the Westinghouse Science Competition many years before. He generously provided me with more than the mere photo op that the other finalists had received.

During my more recent visit, I again enjoyed observing the offices where policy is made. The room dedicated to the House Committee on Science and Technology is in the Rayburn House Office Building. The representatives sat in the back and we “witnesses” sat facing them. Inspirational plaques hung above the representatives’ heads, the first of which read “WHEN THERE IS NO VISION THE PEOPLE PERISH. Proverbs 29:18.”

It seems American government must refer to scripture even in the congressional room explicitly dedicated to science and technology. The line nonetheless expresses a noble and accurate sentiment, which we all would like to apply.

The second plaque contained a more secular quote from Tennyson: “FOR I DIPPED INTO THE FUTURE, FAR AS MY EYES COULD SEE / SAW THE VISION OF THE WORLD AND ALL THE WONDER THAT WOULD BE.”

That was also a nice thought to bear in mind while describing our research goals.

The irony was that the room was arranged so that we “witnesses” from the science world—who already were sympathetic to these statements—faced the plaques, which hung directly in our line of view. The representatives, on the other hand, sat underneath the words so they couldn’t see them. Congressman Lipinski, who in opening statements said that discoveries inspire more questions—and large metaphysical inquiries—acknowledged that he used to notice the plaques but they were now all too easy to forget. “Few of us ever look up there.” He expressed his gratitude for being reminded.

Moving on from the decor, we scientists turned to the task at hand—explaining what it is that makes this such an exciting and unprecedented era for particle physics and cosmology. Although the representatives’ questions were occasionally pointed and skeptical, I could appreciate the resistance they constantly face in explaining to their constituents why it would be a mistake to stop funding scientific work—even in the face of economic uncertainties. Their questions ranged from details about the purposes of specific experiments to broader issues concerning the role of science and where it is heading.

In between the absences of the representatives, who periodically had to leave to vote, we gave some examples of the side benefits accrued by advancing fundamental science. Even science intended as basic research often proves fruitful in other ways. We talked about Tim Berners-Lee’s development of the World Wide Web as a means of letting physicists in different countries collaborate more readily on their joint experiments at CERN. We discussed medical applications, such as PET scans—positron emission tomography—a way of probing internal body structure with the electron’s antiparticle. We explained the role of the industrial-scale production of superconducting magnets that were developed for colliders but now are used for magnetic resonance imaging as well, and finally the remarkable application of general relativity to precision predictions, including the global positioning systems we use daily in our cars.

Of course significant science doesn’t necessarily have any immediate benefit in practical terms. Even if there is an ultimate pay-off, we rarely know about it at the time of the discovery. When Benjamin Franklin realized lightning was electricity, he didn’t know electricity soon would change the face of the planet. And when Einstein worked on general relativity, he didn't anticipate it would be used in any practical devices.

So the case we made that day was focused primarily not on specific applications, but rather on the vital importance of pure science. Though the status of science in America might be precarious, many people currently recognize its worth. Society's view of the universe, time, and space changed with Einstein—as the original lyrics of "As Time Goes By" quoted in *Warped Passages* attest to.[3] Our very language and thoughts change as our understanding of the physical world develops and as new ways of thinking progress. What scientists study today and how we go about this will be critical both to our understanding of the world and to a robust and thoughtful society.

We are currently living in an extraordinarily exciting era for physics and cosmology, with some of the edgiest investigations ever proposed. Through a wide-ranging set of explorations, *Knocking on Heaven's Door* touches on our different ways of understanding the world—through art, religion, and science—but chiefly with a focus on the goals and methods of modern physics. Ultimately, the very tiny objects we study are integral to discovering who we are and where we came from. The large-scale structures we hope to learn more about could shed light on our cosmic environment as well as on the origin and fate of our universe. This book is about what we hope to find and how it might happen. The journey should be an intriguing adventure—so welcome aboard.

Part I: SCALING REALITY

CHAPTER ONE

WHAT’S SO SMALL TO YOU IS SO LARGE TO ME

AMONG THE MANY reasons I chose to pursue physics was the desire to do something that would have a permanent impact. If I was going to invest so much time, energy, and commitment, I wanted it to be for something with a claim to longevity and truth. Like most people, I thought of scientific advances as ideas that stand the test of time.

My friend Anna Christina Büchmann studied English in college while I majored in physics. Ironically, she studied literature for the same reason that drew me to math and science. She loved the way an insightful story lasts for centuries. When discussing Henry Fielding’s novel *Tom Jones* with her many years later, I learned that the edition I had read and thoroughly enjoyed was the one she helped annotate when she was in graduate school.[4]

Tom Jones was published 250 years ago, yet its themes and wit resonate to this day. During my first visit to Japan, I read the far older *Tale of Genji* and marveled at its characters’ immediacy too, despite the thousand years that have elapsed since Murasaki Shikibu wrote about them. Homer created the *Odyssey* roughly 2,000 years earlier. Yet notwithstanding its very different age and context, we continue to relish the tale of Odysseus’s journey and its timeless descriptions of human nature.

Scientists rarely read such old—let alone ancient—scientific texts. We usually leave that to historians and literary critics. We nonetheless apply the knowledge that has been acquired over time, whether from Newton in the seventeenth century or Copernicus more than 100 years earlier still. We might neglect the books themselves, but we are careful to preserve the important ideas they may contain.

Science certainly is not the static statement of universal laws we all hear about in elementary school. Nor is it a set of arbitrary rules. Science is an evolving body of knowledge. Many of the ideas we are currently investigating will prove to be wrong or incomplete. Scientific descriptions certainly change as we cross the boundaries that circumscribe what we know and venture into more remote territory where we can glimpse hints of the deeper truths beyond.

The paradox scientists have to contend with is that while aiming for permanence, we often investigate ideas that experimental data or better understanding will force us to modify or discard. The sound core of knowledge that has been tested and relied on is always surrounded by an amorphous boundary of uncertainties that are the domain of current research. The ideas and suggestions that excite us today will soon be forgotten if they are invalidated by more persuasive or comprehensive experimental work tomorrow.

When the 2008 Republican presidential candidate Mike Huckabee sided with religion over science—in part because scientific "beliefs" change whereas Christians take as their authority an eternal, unchanging God—he was not entirely misguided, at least in his characterization. The universe evolves and so does our scientific knowledge of it. Over time, scientists peel away layers of reality to expose what lies beneath the surface. We broaden and enrich our understanding as we probe increasingly remote scales. Knowledge advances and the unexplored region recedes when we reach these difficult-to-access distances. Scientific “beliefs” then evolve in accordance with our expanded knowledge.

Nonetheless, even when improved technology makes a broader range of observations possible, we don’t necessarily just abandon the theories that made successful predictions for the distances and energies, or speeds and densities, that were accessible in the past. Scientific theories grow and expand to absorb increased knowledge, while retaining the reliable parts of ideas that came before. Science thereby incorporates old established knowledge into the more comprehensive picture that emerges from a broader range of experimental and theoretical observations. Such changes don’t necessarily mean the old rules are wrong, but they can mean, for example, that those rules no longer apply on smaller scales where new components have been revealed. Knowledge can thereby embrace old ideas yet expand over time, even though very likely more will always remain to be explored. Just as travel can be compelling—even if you will never visit every place on the planet (never mind the cosmos)—increasing our understanding of matter and of the universe enriches our existence. The remaining unknowns serve to inspire further investigations.

My own research field of particle physics investigates increasingly smaller distances in order to study successively tinier components of matter. Current experimental and theoretical research attempt to expose what matter conceals—that which is embedded ever deeper inside. But despite the often-heard analogy, matter is not simply like a Russian matryoshka doll, with similar elements replicated at successively smaller scales. What makes investigating increasingly minuscule distances interesting is that the rules can change as we reach new domains. New forces and interactions might appear at those scales whose impact was too tiny to detect at the larger distances previously investigated.

The notion of scale, which tells physicists the range of sizes or energies that are relevant for any particular investigation, is critical to the understanding of scientific progress—as well as to many other aspects of the world around us. By partitioning the universe into different comprehensible sizes, we learn that the laws of physics that work best aren't necessarily the same for all processes. We have to relate concepts that apply better on one scale to those more useful at another. Categorizing in this way lets us incorporate everything we know into a consistent picture while allowing for radical changes in descriptions at different lengths.

In this chapter, we'll see how partitioning by scale—whichever scale is relevant—helps clarify our thinking—both scientific and otherwise—and why the subtle properties of the building blocks of matter are so hard to notice at the distances we encounter in our everyday lives. In doing so, this chapter also elaborates on the meaning of "right" and "wrong" in science, and why even apparently radical discoveries don't necessarily force dramatic changes on the scales with which we are already familiar.

IT'S IMPOSSIBLE

People too often confuse evolving scientific knowledge with no knowledge at all and mistake a situation in which we are discovering new physical laws with a total absence of reliable rules. A conversation with the screenwriter Scott Derrickson during a recent visit to California helped me to crystallize the origin of some of these misunderstandings. At the time, Scott was working on a couple of movie scripts that proposed potential connections between science and phenomena that he suspected scientists would probably dismiss as supernatural. Eager to avoid major solecisms, Scott wanted to do scientific justice to his imaginative story ideas by having them scrutinized by a physicist—namely me. So we met for lunch at an outdoor café in order to share our thoughts along with the pleasures of a sunny Los Angeles afternoon.

Knowing that screenwriters often misrepresent science, Scott wanted his particular ghost and time-travel stories to be written with a reasonable amount of scientific credibility. The particular challenge that he as a screenwriter faced was his need to present his audience not just with interesting new phenomena, but also with ones that would translate effectively to a movie screen. Although not trained in science, Scott was quick and receptive to new ideas. So I explained to him why, despite the ingenuity and entertainment value of some of his story lines, the constraints of physics made them scientifically untenable.

Scott responded that scientists have often thought certain phenomena impossible that later turned out to be true. “Didn’t scientists formerly disbelieve what relativity now tells us?” “Who would have thought randomness played any role in fundamental physical laws?” Despite his great respect for science, Scott still wondered if—given its evolving nature—scientists aren’t sometimes wrong about the implications and limitations of their discoveries.

Some critics go even further, asserting that although scientists can predict a great deal, the reliability of those predictions is invariably suspect. Skeptics insist, notwithstanding scientific evidence, that there could always be a catch or a loophole. Perhaps people could come back from the dead or at the very least enter a portal into the Middle Ages or into Middle-earth. These doubters simply don’t trust the claims of science that a thing is definitively impossible.

However, despite the wisdom of keeping an open mind and recognizing that new discoveries await, a deep fallacy is buried in this logic. The problem becomes clear when we dissect the meaning of such statements as those above and, in particular, apply the notion of scale. These questions ignore the fact that although there will always exist unexplored distance or energy ranges where the laws of physics might change, we know the laws of physics on human scales extremely well. We have had ample opportunity to test these laws over the centuries.

When I met the choreographer Elizabeth Streb at the Whitney Museum, where we both spoke on a panel on the topic of creativity, she too underestimated the robustness of scientific knowledge on human scales. Elizabeth posed a similar question to those Scott had asked: “Could the tiny dimensions proposed by physicists and curled up to an unimaginably small size nonetheless affect the motion of our bodies?”

Her work is wonderful, and her inquiries into the basic assumptions about dance and movement are fascinating. But the reason we cannot determine whether new dimensions exist, or what their role would be even if they did, is that they are too small or too warped for us to be able to detect. By that I mean that we haven’t yet identified their influence on any quantity that we have so far observed, even with extremely detailed measurements. Only if the consequences of extra dimensions for physical phenomena were vastly bigger could they discernibly influence anyone’s motion. And if they did have such a significant impact, we would already have observed their effects. We therefore know that the fundamentals of choreography won’t change even when our understanding of quantum gravity improves. Its effects are far too suppressed relative to anything perceptible on a human scale.

When scientists have turned out to be wrong in the past, it was often because they hadn’t yet explored very tiny or very large distances or extremely high energies or speeds. That didn’t mean that, like Luddites, they had closed their