Reality in the Shadows

(or)

What the Heck's the Higgs?

S. James Gates, Jr.,
Frank Blitzer, and
Stephen Jacob Sekula

YBK Publishers
New York

Reality in the Shadows or What the Heck's the Higgs?

YBK Publishers, Inc.
39 Crosby Street
New York, NY 10013
www.ybkpublishers.com

ISBN:978-1-936411-39-9

Library of Congress Cataloging-in-Publication Data
Names: Gates, S. James (Sylvester James), author. | Blitzer, Frank, author. |
Sekula, Stephen Jacob, author.
Title: Reality in the shadows, (or), what the heck's the Higgs? / S. James
Gates, Jr., Frank Blitzer, and Stephen Sekula.
Description: New York, NY : YBK Publishers, Inc., [2017]
Identifiers: LCCN 2017054494| ISBN 9781936411399 (pbk. ; alk. paper) | ISBN
1936411393 (pbk. ; alk. paper)
Subjects: LCSH: Physics--History.
Classification: LCC QC7 .G28 2017 | DDC 530.09--dc23
LC record available at https://lccn.loc.gov/2017054494

Manufactured in the United States of America for distribution in
North and South America or in the United Kingdom or Australia
when distributed elsewhere.

For more information, visit www.ybkpublishers.com

Contents

Chapter 1

Cosmology in Motion

Reality in the Shadows chronicles the adventures and research of many who have sought to explore the question, "Just what is the universe?" They observed nature and wrote descriptions of their observations using mathematics, the only human language that is known to be capable of most completely and accurately summarizing their discoveries. While mathematics goes a great way toward quantifying the behavior of the universe, it is a means to *approximate* what is observed about the reality. These mathematical representations are like the shadows on the wall in Plato's *Allegory of the Cave,* in which prisoners face the wall of a cave, unable to turn their heads to see what it is that casts the shadows they see. Their descriptions of what causes these shadows are not always accurate. (Do a Google search on "allegory of the cave" for a more complete explanation.) Sometimes the mathematical statements present inadequate description and at other times they are completely incapable of describing the phenomena. However, each description, hit or miss, inches the observers forward toward a more accurate description of reality that is not yet fully emergent of its mathematical representations.

This process was initiated by a small number of ancient seekers who wanted to understand the universe. This continues today, spurring a relay race of discoveries that spans a period greater than 2,500 years. However, modern science got its real boost after the period of medieval Europe.

Old explanatory frameworks emerged from a questioning among philosophers and religious leaders who thought about life. They rationalized their existence through the worship of creator gods, founded astrological signs, and considered the orbits of the planets that they imagined guided their existence. This they called "natural philosophy."* As time went on, their successors furthered these questions by asking, "Why?"

These questioners became scientists by recording their observations of the heavens and the earth. Galileo Galilei, whom Albert Einstein, (the great physicist, about whom we will hear much more later) described as the father of all science said, "Philosophy is written in this grand book, the universe, which

* Today, natural philosophy has a different name. It is called "physics."

stands continually open to our gaze, but the book cannot be understood unless one first learns to comprehend the language and to read the alphabet in which it is composed. It is written in the language of mathematics…"

In seeking answers to the mysteries of its workings, men and women have endeavored over eons to unveil the universe as it slowly yields itself to study. In setting down the pages of their books, there were times when an expected conclusion resulted from an observation that was not anticipated—a point at which their vision of the universe failed to agree with their observations of it. This recording of expectation, observation, and consequence came to be codified as "the scientific method." It continues today, each time reaching a point when knowledge meets a stumbling block in the forwarding of its understanding of the universe. Science is dynamic, ever changing as the boundaries of knowledge are constantly expanded.

These early individuals were unique because they questioned what they saw as well as *why it happened.* They described these actions using mathematics and performed tests to clarify and support what they saw. Although the tools they devised captured ever more accurate information, the shadows continued to play on the walls of the cave, but the resulting output of this process produced theories (explanatory frameworks with predictive power that led to the discovery of new facts) about the grand working of the universe. All of science is a theory, but not in the sense of it being a collection of guesses. Science gives a most accurate description through the use of logical reasoning about structures that are observable.

Recent observations have determined the age of the universe to be 13.74 (±0.11) billion years; this, according to calculations from the Hubble telescope and WMAP (Wilkinson Microwave Anisotropy Probe) satellite observations.

Do we *really* know how old the universe is? Do we *really* know and understand what holds the universe together—where it is going, how it got here—and what is going to happen to it? Such questions often result in new questions. The WMAP satellite information has since been superseded by more powerful research called Planck, a project of the European Space Agency. Planck tells us that the universe is 13.807 (±.026) billion years old. Still, there is anticipated error in that number. That error factor is called "science," the going forward with continuing research to find even more accurate and precise information.

This book is intended to be a largely non-mathematical guidebook aimed at the more-engaged observer of nature to help in grasping the major ideas and concepts that bring us to the state of modern physics today. Mathematical equations that are used are intended to be illustrations to promote understanding of the manner in which arguments are framed. One need not have an understanding of the underlying mathematics. It is as with music, where one need not read the score of a great concert piece in order to appreciate the majesty of its composition.

The Geocentric Universe

In the time of Aristotle (384 B.C.–322 B.C.), people believed in the geocentric theory—that Earth is stationary and everything revolves around it. Fostered by Aristotle, it describes the universe as a series of concentric circles, each containing one of the five planets known at that time, all revolving around a stationary Earth.

Religion was the primary framework used by early searchers of the universe. Most people were illiterate and relied on learned religious leaders for guidance. Other, perhaps even more accurate, ideas were abandoned in favor of these teachings.

The geocentric concept was accepted because people believed that Earth was placed in a privileged state by the gods, believing that it was the only place in the universe where humans resided. This view remained popular for centuries because it coincided with the early understanding of the universe that was taken from naked-eye observation. It gained powerful support from the early Christian church due to the belief that humanity has a special place in creation. It seemed only logical that Earth was the center stage in the drama of creation. These teachings of the church combined with casual observation made this an enduring, albeit inaccurate, cosmology.

The geocentric theory was codified by Claudius Ptolemy (c. 90 A.D.–c. 168 A.D.), an Egyptian astronomer, mathematician, and geographer who studied the motions of the planets and described them in tables that were used to obtain past and future positions of the planets. He was able to see and plot Mercury, Venus, Saturn, Neptune, and Jupiter (all named after Roman gods). He wrote three treatises during his lifetime, the pertinent one on astronomy called the *Almagest*, "The Great Treatise." Contained in thirteen volumes, it is the only surviving comprehensive treatise on the universe of that time period.

Seeking to fit their motion into a geocentric theory, the planets were shown to traverse very complicated paths called epicycles. Due to a lack of technology, observations resulted in rudimentary data. Across time, many devices were invented to help to understand the planetary motions. Calendars were created to mark the days and years, and instruments were developed to study the stars and planets.

The Heliocentric View

So strong was the geocentric belief of astronomers, clergy, and philosophers in early history, that it was very difficult to propose or support any alternative to this belief. Scientists had a difficult time convincing the learned masters that other possibilities existed and were, perhaps, more accurate. Though the Aristotelian view predominated, there *were* dissenters.

Aristarchus of Samos (310 B.C.–230 B.C.) was the first person to propose a heliocentric universe—the concept that the planets revolve around the sun rather than the earth. Almost 300 years before Ptolemy, and about 1,800 years before Copernicus, he made careful measurements that gave him reason to believe that the earth and the planets revolved around the sun. Unlike his contemporaries, he realized the power that observation has in formulating theories about the stuff of reality. From his observation of eclipses he concluded that the radius of the moon was half that of Earth and that the distance from the earth to the moon was about 57 times that of the earth's diameter. That said, due to the inadequacies of his methods of observation, both of these answers were incorrect by a factor of about two, but the concept was accurate.

Eratosthenes of Cyrene (276 B.C.–194 B.C.), following the same kinds of logic as Aristarchus, deduced that the earth, like the moon and sun, was spherical in shape. Using geometry and calculating observations of the sun at the time of the summer solstice, he calculated the size of Earth to within only a few percent of today's measurements!

But the views of Aristarchus fell on deaf ears because most educated people continued to follow the teachings of those clergy and philosophers who believed strongly in the geocentric view. These remarkable achievements found little acceptance during the lifetimes of Aristarchus and Eratosthenes. Their critics were able to all but silence these dissenters.

Though their works were judged by their contemporaries to be incorrect, these scientists understood that using mathematics (in this case, geometry) in concert with observation could yield a more accurate view of the universe. This history holds a valuable lesson—as science advances through the work of individuals, the establishment will not necessarily embrace concepts that will produce progress . . . at least not at first. At this point, the Greeks and Romans were more mathematical philosophers than scientists.

Without a means of noting and cataloging planetary movement over long periods of time, it would be impossible to demonstrate that the heliocentric universe provided an accurate representation of the universe. Their ideas languished for centuries, largely unpursued by others.

Although there were others who came to the same conclusions as did Aristarchus and Eratosthenes, it was dangerous to assert beliefs different from the accepted religious edict. Giordano Bruno, a catholic priest, was martyred in 1584, in part for publishing his assertion that stars are other suns, circling around which were other planets like Earth, that might carry intelligent life. Those who denied arguments based on well-reasoned mathematical models created by observation of our cosmos, held sway for centuries—but the universe ultimately pays no heed to denialism.

A Major Scientific Revolution

Although early scholars had published heliocentric hypotheses centuries before Nicolas Copernicus (1473–1543), his publication of a scientific theory of heliocentrism, demonstrating that the motions of celestial objects can be explained without putting Earth in the center of the universe, stimulated further scientific investigation. It became a landmark in Western science known as the Copernican revolution. Enthusiasts focused on the quest to fathom the marvels of the universe. In doing this, a body of work emerged from the minds of a few contributors that set down the basic principles of the early universe. These contributions are accepted even today. These were the titans of science, who contributed significantly to our current understanding of the universe and made it possible for their followers to probe deeply into its workings.

Nicolas Copernicus

The geocentric theory continued to be believed until the 15th century, when Nicolas Copernicus appeared on the scene. He became the first astronomer to formulate a scientifically based heliocentric cosmology that removed Earth from the center of the universe. His book, *De Revolutionibus Orbium Coelestium* ("On the Revolutions of the Celestial Spheres"), is often regarded as the starting point for modern astronomy and the defining epiphany that began the scientific revolution. He published this work on his deathbed, fearing to be ridiculed (if not worse) during his lifetime. His research set down tables to show how the planets revolved around the sun in circular orbits, as illustrated in Figure 1.1. For the first time the world was given quantified evidence that Earth was not at the center of the universe, but just another planet that circled the sun.

This revelation sparked a major revolution around the world, greatly influencing interested observers and scientific experts such as Tycho Brahe, Johannes Kepler, Galileo Gallilei, and Isaac Newton, whose combined imaginations fueled the explosion of modern science.

Just as did other contributors to the Renaissance, Copernicus was multifaceted as an astronomer, physician, Catholic cleric, and more. Though one of his many studies, astronomy, was but an avocation, it made its mark on the world stage. It set down in great detail (for the first time) specific data

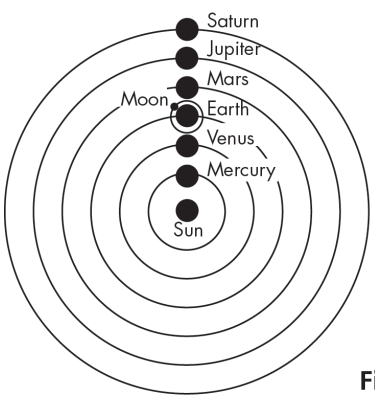

Figure 1.1 The Copernican Heliocentric Model

describing the motions of the planets in our solar system and their relationship to Earth's orbit.

Brahe and Kepler

Tycho Brahe (1546–1601) and Johannes Kepler (1571–1630), following on the heels of Copernicus, furthered the results of their predecessors. They advanced stellar observation and posted new findings of planetary motion even without the aid of a telescope, the invention of which was still to come. The results of the observations of Brahe and Copernicus were analyzed in detail by Kepler. This enabled Kepler to create a mathematical formalization of planetary motion that his predecessors had observed and set down. This was accomplished using mathematics to create a detailed analysis that concluded that the geocentric concept of the universe was incorrect; that Earth and the other planets revolved around the sun. Although these findings were formally published, their theories found no wide acceptance during their lifetimes.

Fascinated with astronomy at age thirteen, Tycho was coaxed by his uncle to enter college at the University of Copenhagen to study law and philosophy. At this impressionable age, an event took place that changed his life—a partial eclipse of the sun.

Brahe became obsessed with astronomy, putting aside the law and philosophy. He bought books and instruments and stayed up much of each night studying the stars. When he was seventeen he observed a special event—Jupiter and Saturn passing close to each other (August 17, 1563). He found on checking the data that the Alfonsine tables (which contained positioning information for the sun, moon, and planets, first published in 1483 and updated for about three hundred years after) were off by a month in predicting this event, and the Copernicus tables were off by several days. Tycho determined that this was unacceptable; that much better tables could be constructed through more accurate observation over an extended period of time. He decided that this was what he was going to do.

Tycho returned to Germany, falling in with some rich amateur astronomers in Augsburg. He persuaded them that what was needed was accurate observation. This required the use of large quadrants to obtain lines of sight on stars. This is shown in Figure 1.2, being a device having a nineteen-foot radius, probably made of logs, that defined one-quarter of a circle. It was graduated in sixtieths of a degree. There were 1350 divisions in each 22.5-degree sector of the quadrant. Thus, each division on the quadrant had a value of 0.01667 degrees of circumference—a *very* accurate protractor.

This device made it possible to make very accurate observations of the positions of the planets and other celestial bodies such as the moon by sighting along the lines marked out on the quadrant's circumference. From the data he developed, Brahe created his own model of the universe, which he published late in the 16th century.

is a special number in the world, the ratio of the circumference of a circle to its diameter; it's special because it has never been observed to repeat sequences of digits to any decimal place at any length to which it is computed. Although the significance of this number was known to ancient Egyptian, Babylonian, and Indian mathematicians before Archimedes, his first accurate determination of its value led some to call it "Archimedes' Constant."

Like a message in a bottle, the "Archimedes Palimpsest" began its reemergence in 1840. A palimpsest is a page from a book or scroll that has been scraped off and re-used. Many palimpsests are made from the well-processed hides of animals making them more durable than paper. In medieval Europe, when paper was rare, the practice of washing a palimpsest of its characters and reusing it for new text was common. A Biblical scholar, Constantine Tishendorf, visiting Istanbul in 1840, came across a palimpsest that contained Greek mathematical symbols. In 1906, Johan Heiberg had pages of that palimpsest photographed and published. Another scholar, Thomas Heath, translated the Greek and in 1971 an Oxford Professor, Nigel Wilson, realized that it was the lost Archimedes Palimpsest. The Archimedes Palimpsest now resides in Baltimore's Walker Art Museum. Eventually, using modern technological means, including a particle accelerator at the SLAC National Accelerator Laboratory (formerly known as the Stanford Linear Accelerator Center), and teams of scientists, it was found that the palimpsest contains seven mathematical works of Archimedes:

(a.) Equilibrium of Planes
(b.) Measurement of a Circle
(c.) On Sphere and Cylinder
(d.) On Floating Bodies
(e.) Methods of Mechanical Theorems
(f.) Spiral Lines
(g.) Stomachion

In "Methods," Archimedes describes techniques that are recognized today as the first use of integral calculus.

Archimedes was killed by a Roman soldier around 212 B.C. On his headstone is the inscription:

> A solid sphere has 2/3 the volume of a circumscribed cylinder.

This inscription would cause one to conclude that this must be the resting place of a person who knew calculus before Newton or Leibniz.

The Gravitational Force

Newton was elected Lucasian Professor of Mathematics in 1669 at Cambridge University, the chair given to Paul A.M. Dirac in 1932, occupied until recently by Stephen Hawking, who retired in 2008, and currently held by Michael B. Green, one of the co-inventors of superstring theory.

At Cambridge, Newton described his understanding of the physics governing mechanics, the laws of motion, and the laws of optics, using calculus, which he invented for this purpose. Every high school student is familiar with Newton's law of gravitation— that two bodies under the influence of gravity are attracted to each other by a force that is proportional to the product of their masses and inversely proportional to the square of the distance between them.

He analyzed the physics of a body under the influence of gravity in orbit around the sun and determined the dynamical equation that describes an elliptical orbit due to the gravitational attraction between the planet and the sun. This mathematical demonstration supported Kepler's assertion, observing their motion to occur as elliptical orbits. This knowledge made it possible three centuries later for engineers to design and build the APOLLO spacecraft and send it to the moon in 1968. These simple laws have guided civilization for over three centuries and are still valid . . . at appropriate scales. . . for later, Einstein was to show that when objects move near the speed of light, Newton's "cathedral of thought" must be abandoned. Later, another group of physicists would show that when objects are too small, on the order of the size of atoms, Newton's edifice must once more be abandoned. Even today, in everyday situations, which includes most engineering, the work of Newton is a solid foundation.

As time moved forward, physicists worked independently in their individual areas of interest—heat, light, electromagnetism, fluid mechanics, etc. They characterized these phenomena and formalized their behaviors in companion scientific areas, developing and unifying the laws governing them as they sought to simplify the laws so that the mathematics would be elegant. It was difficult to perform experiments because experimental apparatus was mostly not yet developed. It was the same problem that hampered Copernicus, Brahe, and Kepler, but not Galileo, as he had access to the advanced technology of the then-new telescope. As we noted in the case of Brahe, when technology is not up to the needs of a scientist, they will often improve existing technology or invent their own to achieve their aims.

Newton's Law of gravitation was sacrosanct and remained so until Albert Einstein showed it to be incomplete and limited when he replaced it with his laws of relativity in 1905 and 1916. New devices were needed to examine the laws governing the universe. The technologies for such devices would emerge in the 19th and 20th centuries. It is technology that enables science to push back the shadows.

The Electromagnetic Force

By the 18th century, the world of physics was teeming with people searching for the laws that govern nature. They had what appeared to be a good foundation on gravity from Newton's work and they learned about electricity and magnetism through the work of scientists like Benjamin Franklin—who studied lightning, claiming it was electricity. Michael Faraday and James Clerk Maxwell were the two most influential people in the discovery and formalization of the electromagnetic force. Physicists of this era performed numerous experiments to develop an understanding of electricity and magnetism and defined the mathematical relationships and interactions between the two phenomena.

The fact that electricity and magnetism are entwined phenomena became apparent to Michael Faraday (1791–1867) who realized that electricity created magnetism and magnetism, in turn, created electricity. Using this knowledge he developed the principles of the electric induction motor. The electric induction motor demonstrates that electricity and magnetism work together to create electric currents and the forces of repulsion and attraction within wires and magnetic materials. He designed a motor that caused a rotating armature to spin. That motor could drive machinery and, when connected differently, would behave as a generator of electricity, as well. Although Faraday learned how these devices worked, he did not develop a formal mathematical explanation for them.

Maxwell's equations accurately defined how to harness energy to make motors, generators, radios, meters, industrial machinery, and many more things leading even to modern radar, X-ray machines, CAT-scanners, and MRIs. All of these behave according to his equations. To this date, no phenomenon associated with electricity or magnetism has ever deviated from the behavior predicted by Maxwell's equations.

Two American scientists (Richard Feynman [1918–1988] and Carl Sagan [1934–1996], respectively) have said of the work of Maxwell:

> From a long view of the history of mankind—seen from, say, ten thousand years from now—there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics. The American Civil War will pale into provincial insignificance in comparison with this important scientific event of the same decade.

> Maxwell's equations have had a greater impact on human history than any ten presidents.

Although Newton and Einstein are better known today among the public than Maxwell, he is one of the three most highly regarded physicists in the history of the discipline. When Einstein was young he explicitly pointed to both as the models for which he strove to achieve his own accomplishment.

Maxwell had an impact on the thinking of physicists about the nature of reality. From the time that Newton completed his work, there had grown up a general philosophical viewpoint that the physical universe was a place very much like a clock. If one understood how the gears and levers worked, the operation of the clock could be understood as there are no invisible parts in a clock.

First Faraday, and later Maxwell, described aspects of the universe that are not seeable by establishing the concept of the "field." A field is thought of as being an intermediary quantity of physical significance that conveys the influence of one physical object through a region of space to another physical object with no apparent connection within the intervening region. Although a field may be invisible to the human eye, it is no less real than any physical object. It is the field of gravity that surrounds the earth that causes us to be able to distinguish up from down. The gravitational field points between these two directions. The Earth's magnetic field causes compass needles to point to the magnetic north pole. These invisible fields, while not obvious, influence human activity.

Instead of thinking of gravity as the sun magically reaching out to affect the orbit of a planet far away, a "field of gravity" is envisioned that surrounds the sun. It is this field that influences the path of the planet. The concept of the field of gravity solved one of the philosophical problems that had worried Newton. The ability of gravity to reach across space had been called by Newton, "action-at-a-distance." Though he was suspicious of this concept, it worked well enough to explain his rule for gravity and he accepted it.

Gravity and electromagnetism, two of the principal forces of nature, had been discovered and well-documented by the mid-1800s, but the world of the atom was still a great mystery to scientists who wanted to understand the link between tiny atoms and the massive universe. In the search for a unified theory, physicists believed that larger bodies in the universe must be built from smaller objects, atoms. They sought mathematical equations that would allow them to predict the universe's evolution from some set of initial conditions to any future condition—from the small atoms that form us, up to the planetary systems that surround us.

This was a strong continuation of Newton's vision of the universe as a clockwork system. It brought with it an inference that the key to a comprehensive understanding of the universe could be found by linking the small elements studied in the chemistry of that time with the methods that were successful in cosmology. This led to work by a group of scientists and especially chemists who searched for the minute particles that defined all matter.

The study of the atom, which began in the chemical industry, became the focal point of new research. The work of both physicists and chemists would contribute significantly to understanding the atom. In the 1700s, new work in chemistry led to the discovery of hydrogen by Henry Cavendish in 1756 and oxygen by Joseph Priestly in 1774.

In the 1860s, Dmitri Ivanovich Mendeleev (1834–1907) noted that the chemical elements had properties that correlated with their mass, leading him to create the periodic table of the elements in 1869, cataloging the first 63 atomic elements by their increasing mass, the number of electrons, and other chemical properties. The table has now been expanded to include more than 100 chemical elements.

The Structure of the Atom

In the 1800s little was known about the world of the small—the world of the atom. Chemists explored the behavior that describes the interactions among atoms. This was a kind of practical knowledge about the bulk behavior of atoms. It allowed the creation of new compounds and new materials having unexpected properties. These behaviors were related to how chemical elements combine by sharing electrons in their outer energy shells. The nuclei of atoms would eventually be known to contain protons and neutrons, accounting for the weight of substances, and electrons, the particles that share the atom's outer energy shells to create the compounds of chemistry.

Chemists were led to greater understanding of atomic behavior through the experiments they performed. By the 18th century, knowledge beyond gravity and electromagnetism gave way to the vigorous pursuit of atomic structure. Information about the nuclear forces of nature began to emerge from this research. By the end of the 19th century, both chemists and physicists believed that the atom was the fundamental particle of all matter—that it was indivisible. They would later learn that the atom was composed of smaller subatomic particles held together by very strong nuclear forces.

As chemists sought for a better understanding of the atom to help them design and build better products, physicists sought understanding of the atom from a purely scientific standpoint, believing that in understanding the lowest common particle of matter, the atom, it would aid them in unifying the laws of the universe. It would help them in understanding how the universe developed and of what it was composed.

Experiments performed in the late 1800s concerning the phenomenon of "natural radioactivity" revealed previously unknown instabilities in the atom that did not follow Newtonian law. The constituents of atoms—electrons, neutrons, and protons—would similarly be found to not behave like larger objects. While the electric charge of the electron is attracted to the positive charge of the proton, they are affected in their motion as well by having spin properties that need to be taken into account. These and similar unusual findings became the foundation of a new science that described particle interaction and behavior—particle physics.

This new field of research became an additional elusive character (a shadow) among the physical laws of nature. Work began in the early 1900s to make sense of these strange occurrences, and continued throughout the 20th century. Particle physics became a major thrust in the sciences of the 20th century, leading to nuclear science, atomic experimentation, and to the atomic bomb—research that truly changed history.

The Universe of the Small

When particle physics was in its infancy, hundreds of scientists were drawn to it. Many questions for research emerged from the experimental results derived to think of these minute parts of nature as either a cloud of probabilities or a particle. We now know that protons and neutrons, the basic constituents of the nucleus, can be described as combinations of other components (sub-atomic particles) called quarks.

The standard model, to be detailed later, is considered to be the culmination of quantum thinking. The physics community believes that, to be pursuable, any successor quantum theory must include the standard model. The standard model accurately describes the observation of particle interaction with the forces of nature in real-world terms. Thus, the results found in the standard model must be reproducible by any greater following theory.

In comparison to the science of the small, the universe has been increasingly better understood by large-scale studies of phenomena such as black holes and dark matter. Investigating observable physical objects such as galaxies (and speculative ones like worm holes), and a large array of celestial objects has enabled physicists to understand the cosmology of the universe while simultaneously advancing their understanding of the micro-universe.

Particle physics and astronomy, as two perspectives on radically different distance scales, have revealed both truths and mysteries in our universe. As we will see later, string theory seeks to unite these two disparate scales into a singular framework. However string theory remains elegant mathematics having no discernable or unique consequence on the observable cosmos, while the study of the sub-atomic and the study of the cosmological, each enjoy a level of precision observability that makes them daily useful tools.

Newtonian Physics

Newtonian physics has been the most instrumental form of study to date in advancing the science needed to understand the universe. Isaac Newton undertook the scientific approach of observation, theoretical description, mathematical analysis, and experimentation as his method for rigorous research in science. Newton's accomplishments and the equations and laws he defined continue to be valid today (within everyday domains) for most physical phenomena that occur on Earth.

His laws of classical mechanics are simple:

First Law: A body in uniform motion (at a constant speed and direction) tends to remain in motion at that speed and in that direction unless acted upon by an unbalanced force. (The law of Inertia)

Second Law: The relationship between an object's mass, m, its acceleration, a, and the applied force, F, is defined by the relation $\boldsymbol{F} = m \times \mathbf{a}$. Acceleration and force are vectors having both magnitude and direction (as indicated by their symbols being displayed in bold italic type); for this force vector the direction of the force is the same as the direction of the acceleration.

Third Law: For every action there is an equal and opposite reaction.

The first law recognizes Galileo's concept of inertia. It states that every body has a property that makes it tend to resist a change in motion or a change in direction. The smaller the body, the more easily it can change direction, but a large body, like a huge ship, tends to resist changing its direction. All bodies have inertia given by their mass, which causes them to resist changes in motion. What we call mass, a measure of the substance of matter, is also a measure of resistance to changes in motion.

The second law of motion is the most powerful of the three laws, because it allows one to make quantitative calculations describing the dynamics of a problem: how a body's speed, position, and direction change when forces are applied to it. This calculation is then used to describe how the path of an object is affected by the applied force. For example, a baseball moves in a prescribed path that is determined by the pitcher's arm and gravity.

The second law also marks one of the key moments in mathematics and science . . . the birth of differential calculus. Although it is not widely recognized by non-scientists, the second law is actually a statement about calculus! It marked the first time that a mathematical development called differential equations appeared in print. The subsequent work of two other giants of physics, James Clerk Maxwell and Albert Einstein, would not have been possible without this development by Newton.

The third law describes a situation with which we are all familiar: what happens when one steps from a boat onto a dock. Stepping from the boat causes the boat to move in the opposite direction. Rocket propulsion is another example.

Newton went on to define the laws by which objects in the universe are attracted to each other under the influence of the force of gravity as shown by the diagram in Figure 3.1. The two masses shown are attracted by a force attributable to their mass.

The symbol "F_{12}" indicates the force on mass number one caused by mass number two; "F_{21}" indicates the force on mass number two caused by mass number one. Before Newton, no one knew that these two forces must be equal but pointed in opposite directions. In the diagram, the force does not have to be caused by gravity. Newton taught via his third law that it is to apply to all

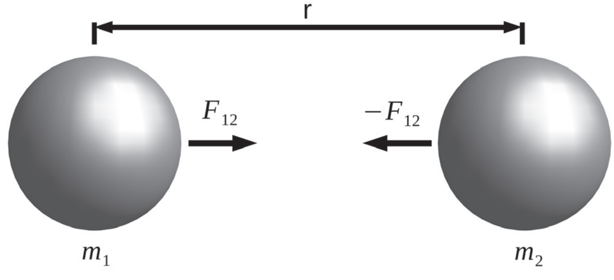

Figure 3.1 Newton's Law of Gravitation

forces, but, as a special case, it can also be applied to gravity. Here he went even farther because he determined how large the forces must be in terms of the size of the masses and their separation.

Law of Gravity: Two bodies are attracted to each other by gravity, a force that is proportional to the product of their masses and inversely proportional to the square of the distance between them.

When expressed as an equation it appears as:

$$F_G = G\,[(m_1 m_2)/r^2]$$

Note that m_1 and m_2 are the two masses, and G is the gravitational constant measured by Newton, given below in metric units

$$G = 6.674 \times 10^{-8} \text{cm}^3/\text{gm-sec}^2 \text{ (metric units)}$$

James Clerk Maxwell (1831–1879), lived and worked in the time between the lives of Newton and Einstein. Though not as widely known by today's public, he is regarded among physicists as an equal to the other two. His legacy is remarkable across a number of areas of physics. For example, he was the first person to understand how the human eye perceives color and made profound contributions to the concepts of heat and entropy, but his most widely felt impact on today's world are the laws that govern the behavior of electricity and magnets. These laws are called "Maxwell's Equations" and they are four in number. They did for electricity and magnets what Newton's laws did for forces, gravity, and motion. Einstein consciously styled himself after Maxwell and was successful in doing for space and time what his predecessors did in other realms, thus moving some of our understanding out of the shadows.

A Man and a Revolution in Physics

Albert Einstein received his doctorate degree in physics in 1905 from the Swiss Federal Polytechnic School in Zurich. He was little known in scientific circles at that time, working as an obscure technical assistant in the patent office. In 1905, the same year in which he received his Ph.D., Einstein published five major science papers. Three of those papers were of great import to our subject; the first on special relativity, the second on the photoelectric effect, and the third in the field of statistical mechanics, elaborating on the work of Ludwig Boltzmann (the Boltzmann constant), relating the pressure and volume of a gas to the number of its molecules and its absolute temperature. Einstein's most famous paper, on general relativity, which defines gravitational influence on the world, the concept of the space-time fabric, and the fourth dimension of time, was published in 1915.

Einstein was well-versed in the ideas of his day, but his distinguishing characteristic as a young physicist was a willingness to set aside grounded assumptions in favor of describing nature as it is, not as people would wish it to be. For instance, Maxwell's equations of electromagnetism described light as a wave moving at a fixed speed through empty space, but the Newtonian view of a wave (a mechanical distortion of a medium) demanded a medium in which the wave (light) moved. This medium was called the "aether." The brilliant physicist, Hendrik Lorentz, (1853–1928) developed a complete mathematical description of the compression of physical bodies as they moved through the aether, in an attempt to resolve some of the paradoxes between the Newtonian and Maxwellian views of physical bodies in motion.

The properties of the aether were well-predicted, and it was sought, its existence to be demonstrated with experiments. These experiments, the most famous by Albert Michelson (1852–1931) and Edward Morley, (1838–1923) failed to detect the aether. Einstein embraced this "null result," accepting that the speed of light, which appeared wholly constant regardless of motion in the Michelseon-Morley experiment, was a universal constant. In doing this, he abandoned the Newtonian notion of time as being absolute and fixed for all observers, which was a key assumption in Newton's original ideas. This preserved Newton's Laws of Mechanics and Gravitation while it sacrificed notions about time and space to provide "room" for new ideas based on the constancy of light.

Einstein recognized that Lorentz's mathematics, developed for describing motion in the aether, worked equally well at relating observations between two observers in motion relative to each other. This was to become known as the famous "Lorentz Transformation," the correct way for two observers to reconcile their independent and differing measurements of space and time by using the constancy of the speed of light. These realizations also led to another of his famous equations relating energy and mass, a recognition that mass is just another form of energy, such as motion or heat.

As a consequence, Einstein discovered the phenomenon of time dilation. Time is analogous to length and mass. The measurements of both of these depend on the frame of reference in which the measurement is taken. That is, both change as the speed of an object changes. When an observer is in motion, measurements of length and duration as they pertain to other objects depend on the speed of the frame where the measurements are being performed; clocks and rulers are affected commensurate with the movement of the frame of reference within which the object is moving.

Relativity

Einstein's theory of relativity stirred up a major controversy in the scientific community. For the first time in three centuries the motion of bodies was being viewed quite differently from that of Newton's understanding. The concepts presented in Einstein's papers on special and general theories of relativity revolutionized existing beliefs about the behavior of the universe:

1. Optical rays from a star passing near a large body (the sun, for example) would deflect (bend) under the gravitational pull of the large body by twice as much as was predicted by the Newtonian understanding of light and motion. Newton wrote in 1704, in his treatise on optics, a prediction that light, too, would be affected by gravity—a consequence of gravity exerting a field of uniform acceleration in a local region of space, independent of the mass of the body, even a massless one!
2. As a vehicle's speed approaches that of light, its clock will slow down (time dilation).
3. As a vehicle's speed is increased, its length, and that of all objects inside it, will contract (get shorter).

To understand these strange effects consider the first assertion. Einstein realized, after his detailed study of the movement of light through space-time and the way that mass can bend space-time, that the degree of deflection of light-would not only be non-zero, it would be twice the degree of that predicted when Newton's notion of space, time, and gravity was used. This was confirmed by astronomer Arthur Eddington, along with his colleague Andrew Crommelin, during the solar eclipse of 1919.

One point to remember is that time dilation happens at all speeds, not just those near to the speed of light. This was tested in 1971 when four ultra-accurate atomic clocks were taken aboard a commercial jet. It was found that clocks that travel indeed do record the passage of time at a different rate than do ones at rest. The results agreed with Einstein's prediction.

At the ordinary speeds experienced by most humans, the changes are miniscule and far too small to notice. What an observer at these speeds perceives as a car passes in the opposite direction, is that it passes at a speed that is the sum of his car's speed and that of the other car ($v_1 + v_2$). If their speeds are both thirty miles per hour, then, the other car is observed to pass at a speed that is the sum of their speeds; sixty miles per hour. However, when the two cars are travelling at the speed of light, the other car passes the observer at exactly the speed of light.

There is no simple summing of speeds at the speed of light. This is due to the aforementioned contraction of space and the dilation of time, which conspire as one speeds up, to maintain the constancy of the speed of light. As one approaches the speed of light, the effect becomes more and more noticeable. The key factor that describes the degree of contraction or dilation is shown below—the Lorentz gamma factor.

As one accelerates, space outside one's own frame compresses in the direction of motion by γ. Also, time outside one's own frame appears slowed by the same degree, γ, so, while space intervals are shorter, time is passing more slowly, canceling these effects on light's observed speed. These characteristics have actually been observed. The first of the three assertions (deflection) was first observed at an eclipse of the sun in 1919. The second of these (clock slow-down, time dilation) was first demonstrated during the 1950s when a satellite carrying an atomic clock was synchronized with one on the ground before launch and, during its orbit, was observed to slow down, as predicted. Today atomic clocks in each of the GPS satellites (there are 24 GPS satellites) are corrected for time dilation by the Lorentz factor

$$\gamma = [1 / (1-v^2/c^2)^{½}]$$

Where γ (Gamma) = Lorentz transformation at the speed, v, in space
ν = Speed of the vehicle
c = The speed of light

As another example, let a body at rest have a mass denoted by the symbol m_0. To compute its "relativistic mass" at a speed v, use the Lorentz factor shown in the equation below. Relativistic mass increases with speed since the energy of motion has an equivalence to mass:

$$m = m_0 [1/ (1-v^2/c^2]^{½}$$

where the symbols m_0 and *v* represent vectors. As we noted earlier, the first person to apply these mathematical ideas was Lorentz, which explains why, to this day, Einstein's work is often spoken of in terms of "Lorentz transformations."

The equation shows that inertia increases as the velocity, *v,* of the vehicle approaches the speed of light, *c*. At the speed of light, inertia becomes infinite. In collider experiments, it is observed that as one accelerates an electron, for example, stronger and stronger electric fields are needed to make the same incremental next-step-up in speed; the inertia of the electron is seen to increase as its speed increases. This theory should not be confused with the Lorentz equation.

There are many strange happenings that have been both predicted and observed. Inertia increases, distances become shorter, and so on. One of the most interesting strange happenings, as we shall soon see, is that Newton's law of gravity is not quite right.

The Equivalence Principle

Albert Einstein sat at his desk as a patent examiner in Switzerland and wondered about many things. On a particular day, after thinking about what would happen to a workman falling off a roof, he had an inspiration. He called it "the happiest thought of my life." He would later recast this idea in terms of "what if I had been in an elevator with no windows?" (like the stick-person in Figure 3.2). What would happen to the man when the elevator accelerated in the downward direction? He concluded that, due to a cancellation of forces, the workman could float freely in the space, weightless. The occupant's feet could

Chapter 4

The Quantum World

By the late 1800s, the behavior of the macro-universe had been well verified to be consistent with Newton's equations. The findings of electromagnetism, heat, light, optics, and the many observations that telescopes revealed were almost all in complete agreement with well-documented physics predictions and equations. By then, physicists had accepted that the universe was composed of atoms (at the smallest scales), comets, planets, stars, nebulae, and many other objects (at the largest scales), and that they operated in accordance with Newton's clockwork processes. Most everyday problems were understood; most questions encountered in the study of nature were solved with the equations of physics. There was growing unanimity of belief among scientists that there was little more that remained to be resolved. Engineers were developing new applications, processes, and products at an ever-increasing rate based on these theories. This demonstrated that science was no longer a matter only for philosophers, but a practical way to increase the quality of human life. Even so, the subject of physics was not considered to be very important in the 1800s. This would change!

Nearly instantaneous communications over huge distances is taken for granted today. Of course, mobile telephoning did not spring forth from nothingness. It was the result of much individual input and in a sense began with four equations. By 1873, James Clerk Maxwell had written equations that describe everything ever observed about electrical and magnetic phenomena. His equations suggested that, were one to arrange magnets, batteries, and wires in the right way, bundles of electromagnetic energy would fly off the wires!

In 1886, Heinrich Hertz built a device to measure those bundles of energy as they, indeed, traveled away from their wires. Many others such as Guglielmo Marconi, Nikola Tesla, Nathan Stubblefield, and even Thomas Edison, pursued physics experiments to create practical radios.

In the late 1800s new knowledge about the atom was revealed every day by chemists creating new compounds. Physicists knew little then about atoms, and among some there was even doubt as to whether they existed. However, questions about the structure and behavior of matter were many.

Physicists were about to open up a field of science that would establish a conceptual framework that would be used to explore and uncover new knowledge about the universe. Let's focus on the quantum realm.

Elementary particles were not generally known to physicists of that time. Chemists were the ones who studied the world of the small. They had to understand elemental behavior if they were to make new products from chemical compounds. Medical science of that period relied on chemistry for medicines and drugs.

Coming upon this scene, an electrochemist, George Johnstone Stoney, began unknowingly to investigate the realm of the atom. In 1891, based on his study of the behavior of gases, he conceived of a "fundamental unit quantity of electricity" that he named the "electron" after discarding the name "electrine." It was that very object that J.J. Thompson would later find in his laboratory in 1897. Stoney also cast his research eye widely on physics issues from planetary dynamics to the theory of gases. Indeed, the Planck mass, the maximum unit of mass, which will play a major role in later chapters, was already in Stoney's mind, although he considered it to be a unit about ten times smaller. Stoney had thereby become the first person in history to conceive of something smaller than an atom, although the size of the atom was unknown at that time.

With no knowledge of an atom's behavior, physicists could not understand how the universe was formed, how the planets and stars got where they are, and how these things interact with the gravitational force. There was much data missing from the description of atoms as posited by chemists because chemists focused on the chemical interaction of elements rather than on their physical substance and the explanation for their behavior.

The Search for the Atom

The existence of the atom as a substantive unit of matter was established by a long process of observation without clear explanation. For instance, working on the masses and other properties of the chemical elements, the chemist Dmitrii Mendeleev (1834–1907) organized the first "periodic table of the elements," a way of looking at matter that made it clear that elements have a pattern of organization about them.

Physicists like Wilhelm Roentgen (1845–1923) and Marie Curie (1867–1934) made fundamental observations about the instability of matter—its ability to spontaneously emit energy that we call "radioactivity." However, at the time they made their observations, they did not yet understand the subatomic processes that contributed to cause this, nor the hidden world of new forces that these behaviors revealed. Albert Einstein, in his "miracle year" of 1905, published an explanation of "Brownian motion," the jittering of dust motes in a drop of water, providing definitive proof that atoms were real. It was atoms, he reasoned, zipping about in random directions next to the dust mote, that sometimes buffet it from the left and sometimes from the right, causing the mote to jitter around. Each of these scientists, and many others, provided pieces of a puzzle, but it would take decades of work for the picture to emerge from those pieces. Let us look at the how-so of this occurrence, starting with the nature of the electron.

Joseph John (JJ) Thomson (1856–1940) was a physics researcher who wanted to understand atomic behavior. He began in 1896 to experiment with what were then called cathode ray phenomena.

Electricity, the flow of charge through solid or liquid material was a well-established and well-understood phenomenon by the time that Thompson began his research. What was curious about cathode rays was that they represented some kind of electrical phenomenon that could traverse even empty space. The cathode ray phenomenon could be produced by placing two metal electrodes inside a high-vacuum chamber, a chamber almost completely devoid of matter. A high voltage was placed at one end (the "anode") and the other metal electrode, the "cathode," was then seen to emit a kind of ray that traveled the empty space between the electrodes and came to the anode.

Thomson exposed these rays to many trials. He noted what happened when one allowed the rays to travel through electric or magnetic fields, observing accelerations and deflections that indicated that they were electrically charged. By carefully measuring these effects, he concluded that they possessed negative electric charge and had a mass about a thousand times smaller than that of a hydrogen ion. These were not atoms, they were something else.

It was George Fitzgerald, nephew of George Stoney, who suggested the name "electron," resurrecting his uncle's ideas about a smallest unit of electrical flow. The name stuck, and to this day we still know this first subatomic particle by this name.

Electrons are also the first particle discovered that represents one of the two known classes of matter. These are quarks and leptons. Electrons are leptons, although their membership as a related class of subatomic particles would not become clear for many decades after Thomson's ground-breaking work.

Thomson realized that he had isolated electrons—small, negatively charged particles, a part of the atom that had been released from the cathode due to the large voltage that had been applied to it. For his work in cathode ray phenomena, Thompson received the Nobel Prize in physics in 1906.

Electrons were thought to move only along wires carrying electric current when under the pressure of voltage from batteries. Chemists had discovered that atoms contain electrons and those electrons appeared to freely exchange place with other electrons in other atoms farther along a wire in a common direction called current.

The Call to Precision

Before we continue with the story of quantum mechanics, let's pause to reflect on the important of the precise understanding of nature. In the late 1940s and early 1950s, Richard Feynman (1918–1988), Julian Schwinger (1918–1994), and

Sin-Itiro Tomonaga (1906–1979), working independently, developed a method for solving the complex mathematics of QED (quantum electrodynamics—how light and matter interact). Feynman approached the problem by developing Feynman diagrams, graphical analogs of the mathematical equations that describe a particle's behavior, making it easier to analyze and solve the equations that describe particle interaction. This technique simplified the complex mathematical rigor needed to analyze particle behavior. Feynman shared a 1965 Nobel Prize with Sin-Itiro Tomonaga and Julian Schwinger.

Quantum electrodynamics extended the understanding that chemists began from their research into chemical reactions. It would now be used by physicists to investigate particle behavior under various influences such as electric fields, magnetic fields, and relativity. It is used to evaluate the characteristics of particles such as their spin, angular and linear momenta, and other behaviors caused by the influence of the forces of nature. QED is simultaneously the best theoretically understood and the most stringently tested-for-accuracy theory in all of physics and in all of history.

As one indication of this, it predicts that electrons possess a property called the "electron anomalous magnetic moment," which means that, in certain ways, electrons behave like magnets. This property of QED is described using a quantity called "g-2" that can be calculated using hundreds and hundreds of Feynman's graphs, calculus manipulations, and computer results, but it is also measurable in the laboratory. Using both approaches, it yields answers that agree with each other to better than one part out of a trillion. There is no other number in all of science where such uniform agreement between theory and experiment has been demonstrated!

So why should one care about such close accuracy? The answer speaks to the dual roles of science in society. One of these roles is to enable the discovery and development of new technologies. As Theodore von Karman (1881–1963), scientist and co-founder of the Jet Propulsion Laboratory once said, "Scientists discover the world that exists; engineers create the world that never was." If scientists do not do their work accurately, then neither can engineers nor technologists reliably develop new products in the realm of nanoscale engineering and its applications . . . think smartphone and tablet computers.

A second role of science is to provide humanity with the means to accurately extend what it knows about our universe. If one wishes to have an accurate understanding of events near to the time of the big bang, for example, one must have the most accurate possible understanding of how things work at the smallest scales. Because, as we have learned, what happened during the big bang continues to affect the universe today and has future implications.

This points to something that is not widely appreciated. Science is a unity, not a disparate collection of belief systems. One cannot with intellectual rigor and honesty accept some parts of it, while simultaneously rejecting other parts. Accuracy in all things drives all of science. Science is able to make predictions only on the basis of accurate measurement compared against the most rigorous logic and mathematics.

Quantum Theory Moves Forward

At the beginning of the 20th century, theoretical physicists, being mostly satisfied that they understood the behavior of the universe as a clockwork process, and believing their quest for understanding nature was almost complete, modified this position as quantum mechanical behavior exhibited itself. With Planck's quantized view of blackbody energy, Einstein's discovery of the quantized photon, Dirac's findings evolving to show that Schrödinger's wave equation could be extended to include Einstein's rules of space-time relativity, and the discovery of the electron, the first subatomic particle, the stage was set for further research into the makeup of the atom and its particles.

There were many mysteries about the atomic realm. Energy, radiating from atoms acted upon by electrical forces, emerges in the form of light, but not all colors (frequencies) of light were emitted by atoms. This phenomenon, "the atomic spectra," would not be understood until a more rigorous model of the atom emerged from Thomson's early model. Further, what differentiated elements from each other? Why is hydrogen, a highly reactive gas, while helium, the next-heaviest element, an inert gas? And, the even more complex question, why are gravity and electromagnetism, the two forces known at the time, so different in character from each other? These issues were unclear at the beginning of the 20th century.

Gravity and electromagnetism are both infinite in range. Separate two masses by greater and greater distances, and one only diminishes their mutual attraction, never quite driving it to zero attraction unless they are an infinite distance apart (an unphysical prospect in a finite universe). Similarly, separate two electrons from each other and their mutual repulsion, due to the sameness of their electric charges, diminishes, but does not vanish except at infinite separation. Yet, the strength of electromagnetism is so much greater than is the strength of gravity on the same distance scale.

For example, a coin-sized permanent magnet can pick up a paper clip even though the paper clip is acted upon by the gravitational force *of every atom that is the Earth!* From this it is clear that gravity and electromagnetism are wildly disparate forces. Why?

The 20th century would bring new questions as physicists explored the mysteries left over from the 19th century. In an era in which physicists probed deeper into the structure of matter than at any time in the past, they learned that the clockwork universe of Newton, with its certainty about the future given the precise knowledge of the past, would have to be abandoned for something far more like the roll of a pair of dice. From this non-deterministic realm of atom and sub-atom would emerge one of the most precise and accurate theories of nature ever devised. To understand how this happened, we must begin with a simple question: what is the atom? Here emerged new mysteries, and from the solution of these mysteries, new understanding about the universe. Unlocking the atom opened our minds to knowing why the stars burn bright in the emptiness of space, how to build new devices like the transistors that are at the heart of every electronic computer, and how to look inside the human body without making a single incision.

The Early Model of the Atom

Scientists, with chemists in the lead, reasoned that atoms contain electrons and protons that were thought to be held together by electromagnetic forces. Later, after the discovery of the neutron, physicists began to wonder about the structure of the nucleus; that protons and neutrons were held together by something about which they knew very little. They surmised that the structure of the atom was determined by fundamental forces in nature. These forces were later defined as the strong nuclear force, (binding protons and neutrons together in the atom's nucleus—as a residual effect of an even stronger force that would later be known as "quantum chromodynamics" or QCD), the electromagnetic force, the weak nuclear force (that influences electrons and particle decay), and the gravitational force.

The strong nuclear force works in the nucleus, keeping protons and neutrons in a stable relationship. The strong nuclear force is the "glue" that holds protons and neutrons together in the nucleus of the atom.

The weak nuclear force influences particle decay. The best example of this is the neutron. If a neutron is placed outside the environment of the nucleus, it will decay (transform) into a proton, electron, and another particle called a neutrino.

Within protons, neutrons and similar nuclear particles, the gluon is the strong-force carrier particle (comparable to the photon that serves as the carrier of electromagnetic force), that imparts unusual behavioral characteristics to quarks (a type of sub-nuclear particle).

The strong force, when quarks are close together, is incredibly strong, overcoming the repulsive electrical forces experienced by grouping positive like-charged quarks closely together. Within this environment, the strong nuclear force acts strangely, behaving like a rubber band or taffy, "slapping" the quarks tightly together and binding them strongly until they are extremely close to each other, requiring very large energies to separate them. When the quarks are extremely close, the force binding them behaves like a rubber band—the tension is removed and relaxed, allowing the quarks to behave almost as if they are free—i.e., not subject to any forces.

The notion that atoms are a fundamental, indivisible particle was long over in the 1930s when it was realized that even the nucleus of an atom could be split. Electrons and protons could be released under bombardment by other particles. Atoms were found to give up matter in the form of beta rays (decaying) as the work of Marie Curie indicated during her experiments with radium and other substances. The theory that the atom was indivisible was disproven by work at Los Alamos and elsewhere showing that splitting the atom would release tremendous energy, just as Einstein had predicted.

The instability of the nucleus of the atom, in light of the strong force that binds protons to protons, protons to neutrons, and neutrons to neutrons, is particularly curious. Radioactive nuclei decay with differing half-lives (the time required for a particle's original radioactivity to fall to half of its intensity). Radium, for example, decays very rapidly—its half-life is short. All known elements (even elements like gold) have unstable isotopes (radioactive forms of the element). In consideration of this, an entirely new science related to weak nuclear force interactions was discovered. It is sometimes called "weak interaction physics."

Early illustrations of the atom looked like the one shown in Figure 4.1, the Rutherford model. This model shows the atom to have a nucleus containing protons and neutrons tightly bound together by the strong nuclear force. Electrons orbit the nucleus like little planets around the sun. The size of the atom was determined to be about 10^{-10} meters (up to a few factors of 10 depending on the number of electrons orbiting the nucleus).

It was thought early on that electrons followed Newtonian rules about the laws of inertia and the electromagnetic force—that they are repelled by other electrons and attracted to the positively charged protons of the nucleus. The "Copenhagen interpretation" (developed between 1924 and 1927 by Niels Bohr and Werner Heisenberg) showed that only the *probabilities* of electron properties such as positional momentum could be determined, while charge can be determined with certainty.

It's Waves, Waves, Waves

In order to grasp the Copenhagen interpretation, which continues to be in use today to understand and explain measurement in the realm of the atom and

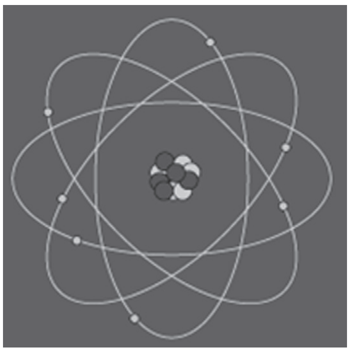

Figure 4.1 The Rutherford Model of the Atom

The Innards of the LHC

You can learn a lot about a tree by studying its rings. The rings of a tree result from the yearly cycles of its growth and slumber. If you look closely at the rings of a single tree, you can even learn about the kinds of struggles it has gone through over its history. The flattening of the rings on one side on just one or two rings might imply that it was struck on that side, perhaps by a hard object. The thickness of the rings can tell you about which were good or lean years for the tree, based on temperature and other environmental phenomena. Much like the rings of a tree, we can learn a lot about a circular particle accelerator by studying its rings.

To feed the accelerator, protons are liberated from hydrogen gas by ionizing the gas. The protons are then injected first into a LINAC. The LINAC accelerates the protons up to 50 MeV. This is not a lot of energy compared to the final energy achievable by the LHC, and brings the protons only to about 5% of the speed of light—the speed of light being the fastest they could ever conceivably travel. This LINAC, known specifically as "LINAC 2," was not built for the LHC; it was constructed in 1978 to provide proton beams to much earlier generations of circular accelerators. This is one of the older "tree rings" of the LHC accelerator complex, designed to intensify proton beams over an earlier LINAC built at CERN.

The LINAC injects these protons into the Proton Synchrotron Booster (PSB), which further accelerates the protons up to 1.4GeV, bringing them to about 83% of the speed of light. Neither was the PSB built specifically for the LHC; it was constructed in 1972 to provide a "boost" in energy to protons emanating from the LINAC before they entered another circular accelerator, the Proton Synchrotron, to be discussed in a moment. Like the LINAC, the PSB is another tree ring in the great complex of machines that feed the LHC. It's an older ring, informing us about an earlier era in proton beam physics.

From the PSB, the protons are injected into a larger circular accelerator, the Proton Synchrotron (PS), which continues the acceleration to 26GeV (99.935% of the speed of light). The PS was also not built just for the LHC. It was its own major accelerator project constructed in the late 1950s and first operated in 1959. The PS is extremely versatile and can accelerate more than just protons. The PS was used to provide protons to earlier projects at CERN, including the first "hadron collider" in the world, the Intersecting Storage Rings (ISR), that ran from 1971 to 1984. It also provided particle beams for a bubble chamber experiment called "Gargamelle," delivering not protons, but a secondarily produced neutrino stream. Gargamelle is famous for detecting subatomic particle interactions that had to be mediated by an electrically neutral particle, but not the photon—it had to be some other neutral, force-carrying particle—one of the foundations of the great discoveries in the early 1980s of the force-carrying particles of the weak nuclear force. We'll talk about the Gargamelle again later.

Note that in each instance of the improvement of the accelerator stages listed above, the leap in energy has been big—the first one was from 50MeV to 1.4GeV, a factor of 28 in energy—but this results in an increasingly modest gain in the speed of the protons (taking them only from 5% to 83% of the speed of light, a gain of just 17—smaller than the gain in energy). The leaps in energy continue, but the gains in speed become ever more modest. This is Einstein's special relativity in action. You can continue to put in more and more energy, making the collision potential of the particles huge, but each major leap in energy results in more and more paltry gains in speed. Particles with mass cannot reach the speed of light. This fundamental behavior of nature is evident in the workings of the pre-accelerator ring systems of the LHC.

From the PS, the protons are injected into the Super Proton Synchrotron (SPS), where they are accelerated to 450GeV (putting them within a tiny fraction—one millionth—of the speed of light, or about 1,500 mph below the maximum possible speed permitted by nature). Again, this accelerator is a "tree ring" in the great CERN accelerator complex leading to entry to the LHC. The SPS was designed to be a frontier energy proton collider, and was the first circular collider to smash protons into anti-protons. The SPS was the machine that produced the collisions for the famous CERN experiments UA1 and UA2, that resulted in the discovery of the W and Z bosons—the carriers of the weak nuclear force. We'll talk about them again, too.

We have reached the end of the history of CERN and about the particle physics that can be told with these ever-larger accelerators. We have finally reached the LHC. The protons delivered from the SPS are accelerated up to 6.5TeV in the main ring of the LHC, which brings them to a speed just 7 mph below the speed of light (99.99999999% of this fantastic speed). They are moving faster than humans have ever before accelerated objects.

There are many independent experiments that operate on the LHC—the beams and the accelerator serve many physics programs, each one operated by hundreds or thousands of scientists and engineers. Now that we have surveyed the ideas and some of the technology and achievements in particle accelerators, let's look at the other side of the problem: once you have successfully made particles collide, how do you identify the debris so you can learn something from the collisions?

Detecting Particle Collisions

If particle accelerators and colliders are meant to provide illumination of the subatomic world, what is it that captures the information occurring in those collisions? For this, one needs particle detectors. Detectors are the complement of colliders. Particle accelerators and colliders are highly complex instruments requiring a devoted, independent team of scientists and engineers to develop, upgrade, operate, and maintain them. Detectors are similarly complex, requiring their own team of scientists and engineers to design, develop, upgrade, operate, and maintain them. Let's look at some basic ideas involved in detection, and some past technologies used to achieve this process. Then we'll look at a modern particle detector and the ways in which these devices push the bounds of present technology.

The basic method of particle detection is this: in front of the particles escaping the point of collision, place layers of material whose job it is to cause the escaping particles to lose energy; capture that energy loss using instrumentation and store the information about the lost energy; develop ways of relating the lost energy back to the kinds of particles that could have lost them, and from this information build a descriptive picture of the debris created by the particle collider.

Much like a forensic scientist analyzing the scene of a multicar accident, the scientist was not there when the accident occurred so there is no first-hand knowledge of the exact details of the accident—which car began it, how it happened, and what was the path of destruction as each car struck the other. The forensic scientist uses the aftermath of the collision to piece together these details, if imperfectly: which car struck first (perhaps based on the one having the most damage, indicating it might have been moving the fastest), and the sequence of car strikes (based on the angles and amounts of damage); the path of destruction, tracking the origin of the accident; and then further clues found at the scene about what might have caused the accident (for instance, debris on the road, or some kind of mechanical failure, or driver error).

Just as in accident scene investigation, experimental physicists, using data from a particle detector, are using their past experience with known particles to interpret the energy losses in material, make best guesses about which particles lost and left that energy, and then track back to find where all the particles came from, thence learning what might have initiated them in the first place. Decades of experience then allows cross-checking their assumptions and inferences, making as sure as they can that they have not misled themselves with wrong inferences.

Let us look at some historical techniques (that have gone through a kind of renaissance in the modern era in looking for dark matter—about which we'll talk more later) followed by a look at more modern techniques for doing the same job, even in the face of far more particles produced at a far faster pace.

A classic technology for seeing traces of subatomic particles as they pass through material is a "cloud chamber" or a "bubble chamber". The ideas are similar in both cases. Cloud chambers contain mists of various liquids, typically water or alcohol while bubble chambers use, not a mist, but a very cold and highly compressed liquid, such as liquid hydrogen.

In a cloud chamber, the mist is caused by super-saturation of a liquid (e.g. 99% pure isopropyl alcohol) in a very cold environment such as dry ice. When a charged particle passes through a cloud (or bubble) chamber, it disturbs the mist (or liquid), allowing one to observe its path as it traverses the chamber. Some cloud chambers are better suited to observe electrons and others are better suited to observe protons (or other charged objects such as those that produce beta rays). The choices one can make in the chemical content of the vapor determines the type of particle that will be observable.

The invention of the cloud chamber is credited to a physicist from Scotland named Charles Thomas Rees Wilson (1869–1959). The technology and scale of these chambers was improved over decades, and by the time of the explosion in theoretical and experimental work in quantum mechanics that took place in the very early 1900s, the cloud chamber was a tool-of-choice for probing deeply into the subatomic world. Cloud chambers allow chemists and physicists to study nuclear radiation, the energetic particles ejected from atomic nuclei when instabilities are induced by the nuclear forces. The cloud chamber was central in many particle discoveries, including the positron, the anti-matter counterpart of the electron, that was predicted to exist in 1928 by Paul Dirac (1902–1984) and found by Carl Anderson (1905–1991) in 1932 and the muon, the heavier cousin of the electron, found in 1936 (also by Anderson).

After the invention of the cyclotron in 1929, cloud chambers were used in conjunction with the cyclotron to observe the paths taken by particles under the influence of nature's fundamental forces. While the positron and muon were discovered in cosmic rays, the marriage of the cloud chamber to the particle collider allowed for the discovery of even rarer and harder-to-detect particles. For instance, while the pion—the proposed carrier of the inter-nuclear force binding proton to proton, proton to neutron, and neutron to neutron—was discovered using cosmic rays and a photographic film-based detector technology, the combination of particle accelerator and cloud chamber allowed for the discovery of a strange cousin of the pion—the kaon—in 1947. As the technology for accelerating, colliding, and detecting subatomic particles advanced, the moving frontier revealed more and more subatomic particles. An entire "zoo" of strange creatures, from kaons to lambdas to sigmas, poured forth from the colliders, found by ever-evolving detector technologies.

A modern particle detector combines many technologies, layered in well-engineered structures, to serve the needs of the physics goals of the experiments. For a modern collider-based detector, a goal is to be able to detect multiple kinds of particles, as many particles are produced in each collision. For instance, in the ATLAS detector at the LHC, the design of the detector was driven by the goal of observing the Higgs boson (should it exist at all), studying in more detail the top quark (presently the heaviest-known fundamental particle in nature), while searching for a wide-ranging suite of phenomena that are not described by the standard model, but could represent a more fundamental theory of nature that includes the standard model. The ATLAS detector, like its counterpart, the CMS detector, needed to be able to see the particles that were expected to be produced if theoretical frameworks like supersymmetry or extra

Chapter 6

What the Heck's the Higgs? —Part I

As the story goes, Peter Higgs was driving to the Institute for Advanced Study (IAS) at Princeton, very close to his destination, when he pulled off the road. He was a nervous wreck. He was about to present his recent work on the mass of fundamental force-carrying particles, that included a concept to determine how this mass could come into being. If it was the correct idea—and if he had done his mathematics correctly—this could explain why some forces have very great range (think light, which, undisturbed by matter, can travel forever without stopping) while other forces have a very short range (think the weak nuclear force, which, locked in the nucleus of the atom, was detected only when the odd behaviors of radioactive nuclear decay were detected). He was about to present his work at one of the most renowned institutions for theoretical physics in the world, a place that had been (until his death in 1955) the home of the great Albert Einstein. Freeman Dyson, another famous physicist, had invited him to give the seminar.

It was 1966. Higgs had published his idea two years earlier, in 1964. He was about to have this idea gutted by some of the smartest people in the world, or perhaps it would live to survive another gutting some other day. Such is the life of the scientist—the quest to be correct at the risk of being shown to be very, very wrong. It was no wonder Higgs had pulled to the side of the road.

He gave the seminar. The ideas he presented then, having taken root in 1964, would seep into the basic theoretical framework that was used to successfully describe nature during the next decade—the Standard Model of Particle Physics. All of the implications of his ideas would turn out to be true, as they were substantiated by experiments in the 1970s, '80s, and '90s. But the cornerstone of his idea, that there must be an unknown force-carrying particle in nature, by which, through its interactions, mass is generated, would not be proven correct until July 4, 2012—nearly 48 years after the idea was first presented. Such is the "life of waiting" endured by a scientist.

The Problem with Forces

The phrase "quantum field theory" is used in colleges to warn undergraduate physics majors of the challenges ahead on the road to becoming a physicist. Graduate students who take the course are planning to become theoretical physicists or experimental physicists, or they are masochists. But what is there in life that is worth doing that is always and ever easy? The quantum field theory is the key idea that has led to a super-precise understanding of the quantum realm—so precise that it has led us to one of the most well-known numbers in the universe—the magnetic moment of the electron.

But, although they are so good at what they do, quantum field theories had a rough start. Many theoretical ideas do so in their infancy. Quantum field theories developed out of quantum mechanics and special relativity. They represent an evolutionary step in the quantum idea. If the first step is to describe atomic and subatomic matter constituents via wave behavior, quantizing the values of properties that are associated with those constituents, the next step is to apply the same logic to the force fields that cause matter to affect matter. Often referred to as "second quantization" (although this is a quite outdated and an often-misunderstood term used in modern college courses), it led to a deep understanding of both matter and forces in the manner in which they are used to represent states of nature. While matter is fundamentally different from force (you cannot create or destroy matter, but in interacting via a force field, two matter particles will exchange quanta of the force, requiring force quanta to come into existence, transmit the force, and go out of existence at the end of the interaction) the same theoretical ideas are extended to both.

Marrying quantum mechanics to special relativity led directly to the prediction of anti-matter and showed how spin angular momentum as a basic feature of matter is naturally a part of any such theory, whether you want it to be there or not. Quantizing force fields led to a deep understanding of the electromagnetic force, uniting the ideas of fields of force and quanta of energy (photons, in the case of light) beneath a singular umbrella.

One of the authors of this book, SS, recalls an extremely profound moment in graduate school when his quantum mechanics professor, Dieter Zeppenfeld, at the end of the second semester of the course, showed how second quantization leads to mathematical operations that create and destroy field quanta (photons). If one then imagines an enclosed cavity containing an electromagnetic field, one can ask the question: what is the energy intensity spectrum of photon radiation that would be emitted from such a cavity? He showed that the field theory elegantly reproduces exactly the spectrum of radiation called "the blackbody curve," the very curve whose mysterious properties first kicked off the quantum revolution through the work of a then-young Max Planck (1858–1947). There are often those profound moments in physics when a discovery out of the past paves the way to deeper insight into the cosmos—intellectual left turns in the mathematics that are found out to be supremely true in the light of experiment. These yield, in turn, better explanations for the mysterious phenomenon that started the whole thing in the first place.

As you can imagine, quantum field theory was quite an achievement. It was extremely successful at describing interactions like those found in matter having an electric charge and the given electromagnetic field associated with that charge. The culmination of this was Quantum Electrodynamics (QED), a theory built upon the difficult theoretical work of many physicists including famous individuals like Paul Dirac (1902–1984), Enrico Fermi (1901–1954), Hans Bethe, Sin-Itiro Tomonaga (1906–1979), Julian Schwinger (1918–1994), Richard Feynman (1918–1988) and Freeman Dyson. Truly an achievement, but it did not achieve perfection—when it came to other known forces of nature, such as the nuclear forces, quantum field theories had a serious flaw: their mathematics always predicted that such forces would be infinite in range.

But the nuclear forces are not infinite. They are supremely constrained to distances the size of just a bit more than a "nucleon"— that is just a bit more than the size of a proton or a neutron. The reasons for that confinement had been inferred by physicist Hideki Yukawa (1907–1981): that force carriers of the nuclear forces have mass, or behave as if they have mass. This limits their range, due to the form of the interaction. Yukawa's work appeared in 1934, and made a definitive prediction: to explain the short range of the nuclear force that binds protons and neutrons in the nucleus, the mass of the force carrier would have to be about 100 MeV/c^2. This force-carrying particle was called a "meson," from the Greek for "intermediate." When the muon was discovered later, in 1936, it was at first mistaken for Yukawa's predicted meson—thus the original name for this particle, the "mu meson," (later shortened to muon, which stuck), but is really a misnomer, as muons play no direct role in nuclear interactions

The discovery of the pi meson (or "pion") in 1947 by Cecil Powell (1903–1969), César Lattes (1924–2005), and Giuseppe Occhialini (1907–1993), led to the confirmation of Yukawa›s proposition that the shortness of the nuclear force was connected to massive force-carrying particles. The idea of massive force-carrying particles seemed a reality that could not be avoided.

At that time, the photon was the only known force carrier, and it was massless. The pion, though, seemed to transmit a force, *and it had mass*. Therefore, massive force carriers are something quantum field theory would have to describe.

The problem was that the quantum field theories under development at the time—the ones that would culminate in QED for the electromagnetic interaction and electric charge—could not reproduce this key feature of the short-ranged and massive nuclear forces. Neither the mass, nor the range, seemed within grasp of these powerful mathematical ideas.

It is important to pause at this moment and consider something that is crucial to quantum field theory: symmetry. We've discussed symmetry before. The symmetries that are built into quantum field theories are not easy to imagine, unlike the rotational symmetry of a snowflake that appears the same under certain choices of rotational angle. The symmetries that occur in quantum field theories also have to do with changes introduced to the mathematics that describe matter particles and the force fields. The equations that describe these things remain invariant under those changes. These kinds of symmetries are known as "gauge symmetries." An analogy may help to begin to grasp this key idea.

Consider water. If one leaves it sitting out in a cup in a room for a long time, it reaches the same temperature as the surrounding environment. Hold your finger in the air for a moment just above the cup of water before dipping your finger into the water in the cup. It feels to be the same temperature as the air, right? (Assuming that you really allowed the water to sit out for long enough.) Temperature is a common concept that we learn about from early in our lives ("Here comes dinner. Don't touch the pan. It's hot!"), but very few of us can actually *define* temperature.

Physicists in the 1800s studied heat, and the energy that is associated with heat, and came to understand that what we call temperature is a measure of the energy of the moving atoms in a body of matter. For instance, when water is hotter than our skin (and thus we call it "warm" or "hot"), it's because the atoms in the water are jiggling and jostling at average speeds that are faster than do the atoms in our skin. The opposite is true when something feels cold—the atoms in the "cold" water are jostling more slowly than those in our skin. The skin and water exchange kinetic energy—the energy of motion—when they come together, and your speedy atoms bang into the slower-moving atoms of the water, causing them to speed up, bringing the energies of the two bodies slowly to an identical state of average motion. Such energy transfers are how you make cold things warmer and warm things colder.

What does all this have to do with quantum field theory? Specifically, what does this have to do with *symmetry*, and very specifically with the *gauge symmetry* present in quantum field theories of nature? The answer lies in the *temperature scale*—the system of numbers we associate with different heat energies. Most people in the United States are comfortable with the Fahrenheit scale of temperatures, while most people in other countries are familiar with the Celsius scale. How are people able to communicate information about temperature between the U.S. and, say, Canada, when they use totally different scales of temperature? The answer is *gauge symmetry*.

The key idea is this: water freezes at the same heat energy content, and water boils at the same heat energy content, independent of what scale of temperature a nation uses to describe that content. This is *gauge invariance*. The physical universe and its behavior is not affected by what scale you choose to describe those behaviors. Not only that, but there is a continuous transformation that allows you to relate the two scales, so it doesn't really matter which one you choose (there are good reasons to prefer the *Kelvin* scale over either Celsius or Fahrenheit, but that's a conversation for another book). The independence of physical phenomena from the choice of scale is a core idea of gauge symmetry; in fact, the name of this symmetry, gauge, comes from the idea that the absolute scale on a gauge (an instrument for assigning numbers to behaviors, like a speed gauge or a fuel gauge in a car) doesn't affect the physical phenomenon that the gauge describes—nature is invariant under the choice of your gauge's scale.

So, water boils at the same amount of heat energy regardless of the temperature scale you use. On the Fahrenheit scale, this happens at about 212 degrees F, while on the Celsius scale this happens at 100 degrees C. How does one relate these two scales? Here is the continuous transformation that allows you to do this:

$$T_F = (9/5)T_C + 32$$

You'll note that at some commonly known temperatures, like boiling for water or freezing for water, this formula returns the familiar numbers. On the Celsius scale, water freezes at 0°C, and we see that if you plug 0°C into the formula above you find that, in the Fahrenheit scale, this happens at 32°F— exactly as is known from experience with these scales. This is how you relate any temperature in one scale to the other. As a fun exercise, the engaged reader might try inverting this equation to come to the one that takes a Fahrenheit temperature and returns the equivalent temperature in Celsius.

The gauge symmetries that are found in quantum field theories are quite a bit more abstract than this, but you get the essential idea from this example. If the core equation of a quantum field theory is invariant under a change of gauge using certain properties of the players in the equation, then the theory is said to be gauge invariant. In fact, a delightful feature of the quantum field theories being developed in the 1950s and early 1960s was that they had gauge symmetries in abundance, making calculations quite a bit easier than the earlier more fractured quantum physics.

But the beauty of these theories turned out to be the key to their failure. After all, is the world around you symmetric? If you look eastward, does the world look exactly the same as it does it you look westward? If someone blindfolded you, spun you about in a room, and then removed the blindfold, would you be able to tell whether your final orientation is different from your initial one? This is almost certainly the case—most people don't have rooms that look the same in every compass direction.

Symmetries are broken all the time in the world around us. They are cherished in mathematics because they greatly simplify the labor in using the equations; but, in the case of quantum field theories, they were also incapable of addressing the very problem that physicists wanted to solve in the 1950s and 1960s: the problem of short-ranged forces.

The Standard Model of Particle Physics

In the history of science, with its slow progress stretched over decades or centuries, what happened next happened very quickly. By the end of the 1960s, particle physicists had the basic outlines of a fundamental theory of nature in hand. It contained many attractive features. It united previously disparate forces—the electromagnetic and nuclear forces—in a single framework that seemed even to predict that, as one cranks up the energy, these forces become indistinguishable from each other. This is called “unification”—when previously distinct aspects of nature are revealed to be different aspects of a singular idea, more fundamental than the aspects themselves. It predicted the behavior and nature of the force-carrying particles of the nuclear forces, especially the weak nuclear interaction. It held the ability to generate mass for force-carrying particles, allowing for them to be short-ranged. It preserved the massless photon. It was gloriously predictive. And it has, much to the aesthetic chagrin of many particle physicists, one of the blandest names in the history of science: the Standard Model of Particle Physics.

Do not let this featureless name fool you. The standard model, as it is shorthanded, is the single-most successful description of nature ever constructed by humankind. Its name belies its power, its scope, and its beauty. It is a great example of why it is unwise to judge a book by its cover, or the character of a person by their physical appearance. It’s what’s on the inside that counts!

It is worth taking yet one more historical step before proceeding to the most important predictions of the standard model. In this step, we will meet a few of the key players in the development of the model. The most famous— those who received the Nobel Prize in Physics for the development of what came to be known as the standard model—are Abdus Salam, Sheldon Glashow, and Steven Weinberg.

We almost met Salam and Weinberg a bit earlier, in the discussion of Goldstone’s work. Now it’s time to bring them out of the shadows and into the forefront of this journey. Abdus Salam (1926–1996) was born in the Punjab State in British India (which later, when British India was partitioned in 1947, was split into East and West Punjab, the part of Punjab where Salam was born becoming part of what is now Pakistan). He proved himself an outstanding scholar quite early on, scoring the highest marks ever recorded for the entrance examination into the Punjab University. While he originally pursued the study of literature, his interests were soon hooked by the language of nature—mathematics—and its ability to tell tales of the fabric of reality. Although he was under pressure to teach English, he committed to the study of mathematics and earned his bachelor’s degree in 1944. After trying (and failing) to join the Indian civil service, he earned his master’s degree in mathematics before earning scholarships to study in England. He went on to earn his Ph.D. from the Cavendish Laboratory at Cambridge University. His thesis, which dealt with fundamental work in quantum field theory, specifically QED, brought him to international fame in the physics community by the time it was published in 1951. While pursuing his Ph.D., he solved a problem that had stumped the great minds of Paul Dirac and Richard Feynman—the elimination of troublesome infinities in calculations within the theory of mesons (the messenger particles in the nucleus). Within six months of taking up the problem, he had a full solution. This brought him attention. While at Imperial College in London in 1961, Salam collaborated with Goldstone to prove the conjecture that Goldstone had earlier made about spontaneous symmetry breaking and the appearance of spin-zero particles as a consequence. This transformed Goldstone's conjecture into a full-fledged mathematical theory, referred to as "Goldstone's Theorem," discussed a bit earlier in this chapter.

Salam's work on quantum field theory, symmetry, and the properties of particles in these theories was carrying him toward a culmination of effort in 1968 that would end in the standard model. But also on that trajectory were Sheldon Glashow and Steven Weinberg. Let's meet them.

Sheldon Glashow was born halfway around the world from Salam, in New York City. His parents were immigrants of Jewish heritage who had come to the United States from Russia. He graduated from the Bronx High School of Science, in the very same class as Steven Weinberg, whom we'll meet in a moment! Glashow earned his bachelor's degree from Cornell University in 1954 and his Ph.D. in Physics from Harvard University in 1959. His advisor was the famous physicist Julian Schwinger (1918—1994), whose ideas about symmetry, mass, and force-carrying particles would later inspire Philip Anderson's work on plasmons and symmetry breaking in 1962–1963. Glashow would hold professorships first at the University of California Berkeley (1962–1966) and then Harvard University (1966–).

Glashow had some notable accomplishments in the 1960s. In conjunction with James Bjorken, they predicted that a fourth quark was needed. In 1964, when there was only evidence for three quarks in nature (up, down, and strange), the prediction, a part of the effort to make sense of the "particle zoo," resulted from the decades of particle accelerator and particle detector experiments. The actual discovery of this fourth quark would wait for a decade after its prediction,

The other highly noted accomplishment that Glashow had during that decade was to correctly propose the group of transformations that define the symmetry of the electromagnetic and weak force unification program. Schwinger had already developed models in which electromagnetism and the weak nuclear force are united in a single framework, but Glashow's work added a crucial element to these models: a new particle that transmitted "neutral current interactions" in the nucleus. This particle would come to be known as the Z boson.

What are "neutral currents?" This concept is most easily understood by considering an electromagnetic analogy. Let's say we send two electrons speeding toward one another, but not head-on. They would miss each other by just a little, were it not for their mutual electromagnetic fields. Because they possess electric charge, they excite quanta of the electromagnetic field—photons—and exchange them. In doing so, they interact, and because they are same-charged, they will repel each other. The electrons will scatter away from each other, but will leave their original electric charges *unchanged*. This is a neutral current interaction—the photon, which has no electric charge (is neutral), is exchanged between them as a flow (a current), transmitting the electromagnetic force (repulsion, in this case) between the two electrons, whose electric charges remain intact.

Glashow's work, extending the ideas of Schwinger, led to the prediction that there were such neutral currents in nuclear interactions, specifically those of the weak interaction. It was already known that there were charged currents—currents involving a force-carrying particle with its own electric charge, either positive or negative. But no one had observed neutral currents—this was a definitive prediction of this idea. There must, then, be an associated, new, massive force-carrying particle that transmits this interaction, one that had previously not been detected.

It is time to meet our final player in this part of the story: Steven Weinberg (1933–). Born in New York City, attending the same high school during the same years as Glashow, Weinberg would also go on to earn his bachelor's degree from Cornell University in 1954. He completed his graduate education at Princeton University, earning his Ph.D. in physics in 1957. He earned his first professorship at the University of California-Berkeley in 1960, becoming a lecturer at Harvard in 1966 and serving as a visiting professor at MIT for one year, in 1967. It was during that year at MIT that he completed his own model of unification of the electromagnetic and weak interactions, paralleling the work of Salam and Glashow. The masses of the force-carrying particles were achieved via the spontaneous symmetry breaking mechanism outlined by Brout, Englert, Higgs, Guralnik, Hagen, and Kibble. It possessed the very same symmetry that was proposed by Glashow in 1961. It, too, predicted the existence of a new heavy force-carrying particle—the Z boson—that transmitted a neutral current interaction in the nucleus. The paper in which this work was published has the very unassuming title, "A Model of Leptons." Again, that simplicity belies the beauty of what Weinberg would describe in his mathematical work.

1968 is the year during which all three lines of this work met. What was distinctive about what Salam, Glashow, and Weinberg accomplished was that they had applied consideration to something which need not have had anything to do with the weak interaction, and, in doing so, not only successfully described the weak interaction but also united it with electromagnetism. That core idea was gauge symmetry. It worked spectacularly well for QED, the quantum theory of electromagnetism, but past is not always prologue. Just because an idea works for one aspect of nature is no guarantee that it will work for another.

If one plugs in the W boson mass, now known directly from experiment, and the estimate of the weak mixing angle from the neutrino-scattering experiments, $\theta_W \approx 27$ degrees, one finds that the Z boson mass is predicted now to lie at 89 GeV/c^2—in remarkable agreement with where it would soon be found and concurring with the currently accepted value of this number! UA1 and UA2 knew exactly where to look, and the signatures to look for that were most distinctive and "clean"—the decay of the Z boson into pairs of charged leptons (such as $Z \rightarrow e^+e^-$—an electron-positron pair). They soon obtained evidence for this force-carrying particle. In a fairly rare move, the Nobel Prize Committee quickly awarded the 1984 physics prize to Carlo Rubbia and Simon van der Meer for developing the methods of detection and production of the weak bosons, and for the subsequent discovery of these crucial aspects of nature.

The 1970s and early 1980s began a period during which one confirmation after another was obtained for the standard model. Aspects of both the electroweak interaction and QCD, the theory of the strong interaction, also present in the standard model, were tested during the years and decades following in a long series of experiments at famous colliders like LEP at CERN and the Tevatron at Fermilab. However, despite having determined a large number of the parameters of the standard model, the aspects of the model related to the Higgs boson continued to be shrouded by experimental shadows.

The Higgs Boson

We've left an important character by the way-side for a bit—the Higgs boson. The last time we discussed it, it was a side-effect of the spontaneous symmetry breaking of the vacuum state of the universe, a necessary act to admit the possibility of massive force-carrying particles. It first was mentioned in Peter Higgs's 1964 paper, though at that moment it was vague and ill-formed. The Guralnik-Hagen-Kibble paper, late in 1964, fleshed out the structure of the "Higgs field" in more detail, but it wasn't until a 1966 paper by Peter Higgs that the crown would be placed on this idea of a new particle in nature.

Higgs calculated, for the first time, the decay properties of the Higgs boson. If it is truly a heavy particle, it must decay to other sub-atomic particles. In his 1966 paper, he provided the essential methods that show how a Higgs boson would decay to a pair of heavy vector bosons —like a pair of Zs or a pair of Ws. In fact, decaying to a pair of Zs was one of the ways in which the Higgs boson was first discovered, forty-six years after Higgs published his paper.

The Higgs boson interacting with other particles is, in the standard model, the physical representation of how particles acquire mass. It is the strength of the interaction between a Higgs boson and, say, a Z boson that yields the mass of the Z boson. That strength is what we perceive in nature as "mass." In effect, we trade the question, "what is the origin of mass?" for the question, "what is the origin of the interaction strength between the Higgs and other fundamental particles?"

This may not seem very satisfying at first, but once it is realized that fundamental mass is a consequence of something like "electric charge"—having to do with the properties of the Higgs boson—then mass no longer becomes a separate part of the theory and a more inclusive theory of nature might then very easily explain the Higgs interactions. Two seemingly independent problems—what it is that sets interaction strengths in nature? and what it is that sets masses in nature?— have been traded into just one problem: what it is that sets interaction strengths in nature?

Let's look a little more at this idea that interaction causes mass to appear in nature. We can do this with a helpful analogy. Let's imagine that we are attending a cocktail reception with a large group of young physics enthusiasts who are evenly distributed throughout a large room. These enthusiasts, who had earlier attended a lecture by prominent physicist, Stephen Hawking, are awaiting his arrival at the reception. The guests have been there a while, so they've gotten some snacks and dispersed around the room. They are analogous to the Higgs field—they are everywhere in space, at all points, evenly distributed. The atmosphere in the room is charged with excitement, analogous to the way that the Higgs field carries a net weak hypercharge everywhere with it.

Let us first consider a case where a particle now enters the presence of the Higgs field. Originally without mass, without inertial resistance to changes in motion, we will see how, in this analogy, the particle *acquires* mass by the strength of its interaction with the Higgs field.

Soon, Dr. Hawking enters the room. His entry immediately creates a level of heightened excitement that rapidly propagates through the group. As he moves into the crowd, people jostle to cluster around him to offer their congratulations, slowing him down and making it difficult for him to navigate the room. From our perspective, it might seem as though Dr. Hawking has just acquired a very large mass, making it impossible for him to move with any haste through the room!

The enthusiasts who are very close to him are eager to greet him and to engage him in conversation, while those not as near continue socializing as the dignitary pushes through the clump that is forming around him. As he moves slowly through the party, this clumping phenomenon continues to happen as new groups, in succession, encounter and engage him, while the previous clump of people disperses somewhat evenly back into the room and goes back to its earlier socializing.

This process encumbers Dr. Hawking as he negotiates the room. This is quite like the action that occurs in the Higgs field among the particles of the universe. The clustering of guests around Dr. Hawking increases his inertia as he crosses the room, slowing him down (similar to acquiring mass) and is much like what happens to a particle in the Higgs field as it gains mass. The top quark, for instance, is the heaviest fundamental subatomic particle yet known, with a mass almost 170 times that of the proton and almost 40% heavier than the Higgs boson itself. The top quark is *very* popular in the Higgs field, and this immense popularity (interaction strength) gives it a correspondingly immense mass (inertia, the resistance to changes in motion).

Let us also now use this analogy to see how the Higgs boson manifests as a result of the field. This will illustrate a point we've glossed over before, regarding the relationship between quantum fields and their corresponding field quanta—the particles that are "excitations" of the fields themselves, when the field is present.

As Dr. Hawking enters the room, a rumor of his arrival begins to spread from that entrance throughout the physics enthusiasts in the room. As the rumor spreads, people clump to share the rumor and then clump again to pass it on, transmitting the rumor through the room by the clumping and chattering and de-clumping of people. This effect is similar to the way in which Higgs particles interact to generate mass for fundamental particles in the standard model. The presence of Dr. Hawking in the room causes clumping, but the rumor of Dr. Hawking, even without his presence, causes some amount of clumping that travels through the room as if it, too, were a particle of its own.

This analogy provides a picture of how this operates for the Higgs field, and how the overall Brout-Englert-Higgs-Guralnik-Hagen-Kibble mechanism can now be entirely explained in terms of the Higgs field.

The Higgs field is special. It is represented by a spin-less particle with no electric charge. All other force-carrying particles, the photon, gluon, W, and Z, are spin-1, and are collectively known as "vector bosons." Unlike the fields associated with vector bosons, the Higgs field exists at all points in space-time. Vector fields, on the other hand, come into existence when one of their interactions occurs and go out of existence at the close of the interaction. The vacuum state of the universe is described in the standard model by the Higgs field. Other fields and matter particles are required to interact with the Higgs. It is these unique features of the Higgs field that give it its role in generating fundamental mass in nature.

The strength of interaction of the Higgs boson with vector bosons and with matter particles was the essential ingredient in discovering the Higgs boson. Once the mass of the Higgs boson is set, its interactions with all other particles are also set in the standard model. Much the same as the relationships among W and Z boson masses, the Fermi coupling constant, and the weak mixing angle are fixed by the theory that when the mass of the Higgs boson is known, then by including the masses of the leptons and quarks, this is also true about its interactions with other particles in the standard model.

There is a problem: the standard model makes no specific prediction about the mass of the Higgs boson. This is, in part, what made it so difficult to hunt it down— there is very little guidance, if any, from the standard model about the mass of the Higgs, leaving it to have any value among a wide range of values.

Once the W and Z bosons were found, that denoted the moment when the hunt was really on for the Higgs boson. Knowing the W boson mass precisely, coupled with a measurement of the top quark mass, allowed physicists to place constraints on the expectation of where the Higgs mass should be. But the top quark was not discovered until 1995 when both the DZero and Collider Detector at Fermilab (CDF) experiments announced that they had detected it in proton-antiproton collisions within the Fermilab Tevatron. Precision measurement of the W mass would have to wait for the LEP experiments at CERN and a later, second run of the Tevatron at Fermilab in the 2000s.

In the 1980s, after the success of the SppS at CERN (and with their later focus on the LEP program in the 1980s and 1990s), CERN began pursuing construction of a larger proton collider that would be designed to cover the huge range of possible masses for the Higgs boson. This was the Large Hadron Collider, which first created physics-quality data in 2010 and required almost thirty years to conceive of, plan, and build. It was designed to provide 7 TeV of energy to each of its twin proton beams.

Also in the 1980s, the first reviews of the United States Superconducting Supercollider, planned at 20 TeV of energy for each of its twin proton beams were begun. That project began construction in the 1990s, but was canceled by the U.S. Congress on October 31, 1993. At that point, it became clear that unless the Higgs boson could be found at the LEP2 collider in the 1990s, or by the Tevatron during its second run in the late 1990s/early 2000s, the world would have to wait for the LHC to come on line in the 2000s.

Indeed, the physicists at the ALEPH, DELPHI, L3, and OPAL experiments at LEP2, and the CDF and DZero experiments at the Tevatron's Run 2 phase, made incredible progress toward discovering the Higgs boson. The theoretical physics community was not idle, either, conceiving of new ways that the Higgs boson might be produced at each collider or conceiving of new techniques for separating even a faint signal of the boson at any experiment. Not knowing what its mass would be, the community devised ever-more complex means of searching for it at higher and higher masses as their colliders raised energies or operated at higher intensities (or both). This was an incredible period during which new experimental and theoretical techniques were devised and the use of advanced statistical and computational methods in the particle physics community boomed.

It would not be until the LHC began operations in 2010 that the kind of data would begin to be available to definitively enable the discovery of the Higgs boson. Let's look at how this was done at the LHC, both in producing the Higgs boson and then observing its decay using the particle detectors, ATLAS and CMS.

Higgsdependence Day

What follows is the personal, first-hand recollections of one of the authors (SS), who was present in the room on the day that the discovery of a temptingly Higgs-like particle was announced at CERN in 2012:

with the unification achieved in the standard model—to fully define gravity's interactions with matter particles in a quantum mechanical manner.

There are presently many open issues about general relativity that make it impossible to achieve unification. Let's consider one of these. Recall that Einstein's equations take advantage of Riemann's metric tensor. Although a natural for describing gravity, this mathematical construct—used to create a description of the gravitational force based on the curvature of space-time and the matter density of the universe—is drastically different from the mathematics that provides the foundation of the standard model. Blindly rushing ahead to create a quantum version of general relativity is the equivalent of taking a square mathematics and cramming it into the round holes of a totally different mathematical framework. It is going to make a mess!

The Twentieth Century Transition

The standard model, with its particles shown in Figure 8.1 (see page 148) is, perhaps, the greatest paradox in science. On one hand, it has been tested many times and found to pass every examination. In some areas, its predictions match those of observation to better than one part in one billion. There are no other such statements that can be made in any other area of science in which experiment and theory have been so rigorously tested and found to agree. The large number of particles and force carriers within the standard model, and the forces it describes, are quite accurately consistent with quantum physics—at least with respect to three of the four known forces of nature.

By the end of the twentieth century, the standard model stood as an accomplishment par excellence. It gave (and continues to give) a quantitatively successful model of the behavior of the physical universe of subatomic particles and forces. It is solidly accurate and has had more testing through experimentation than has any other piece of science . . . *ever*. It describes quantum mechanics with great precision, inferring how the early universe behaved from a time just shortly after the big bang right up to this very time, a span of 13.8 billion years.

That said, the standard model is known to be incomplete as it does not incorporate gravity, nor does it explain the composition of dark matter, and it grossly overshoots on the prediction of dark energy (among its many other flaws). To put that last issue in perspective, all of the beautiful machinery of the standard model—gauge symmetry, spontaneous symmetry breaking, and field theory—comes together to predict the existence of the Higgs boson, but then, when applied to the energy of empty space, it disagrees with the observed effect by more than one hundred and twenty orders of magnitude! This has been called the worst prediction of physics in all history. How do we reconcile this paradox?

Where the standard model and general relativity might begin to intersect, concerns the idea of mass. In the standard model, fundamental mass is intimately tied to the Higgs boson. Without the Higgs, all quarks, leptons, and vector bosons would be massless. Mass does come from places other than interaction with the Higgs boson, something that is also explained in the standard model. However, the reason for disparities in masses—the masses of different quarks, for instance, or the masses of states made from quarks—is not well understood. For instance, the mass of the proton and neutron is not due to the Higgs boson, because the quarks that make up these particles are very light compared to the mass of the resulting bound state. Protons and neutrons are mostly made of gluons, and gluons are massless force-carrying particles. So how is it that protons and neutrons can have masses that are hundreds of times larger than their heaviest constituents?

This is one of the beautiful tricks that nature plays, summarized in Einstein's famous equation, $E = mc^2$. The binding energy of the gluon manifests as the mass—the inertia, the resistance to the change in the state of motion—of the proton and neutron (and any other such bound states of quarks). So, when we speak of the mass of, say, an atom, we have to recall that more than 99.9% of the mass of an atom is derived from its nucleus, and nearly all of the mass of the nucleus arises from the binding of gluons and quarks, not the mass of the quarks. In the scheme of the kind of mass that general relativity cares about, the masses of planets, stars, galaxies, galaxy clusters, and such, better than 99.99% of that mass has nothing to do with the Higgs boson. Einstein taught us that mass is an important attribute of gravity. Yet there is no apparent relation between the Higgs particle and gravitation! Yet, without the Higgs boson, the universe simply ceases to be. There can be no stars or planets, and likely, no clumped material structure at all.

So there is a place where the standard model, with its quantum realm, and the theory of general relativity, with its space-time fabric interacting with matter and energy, may intersect—extreme mass. If one could create a quantum state of extreme mass—masses capable of observably warping space-time—while preserving the quantum aspects of wave behavior and field theories, we might have a playground within which to learn how gravity and the other forces of nature intersect with each other. Perhaps this means firing enough energy into a subatomic particle to pierce the veil of our three dimensions, where gravity is weak, and to expose the other dimensions of space, where gravity might be very strong. Perhaps this could be at the edge of a black hole, where gravity is so strong that not even light can disobey its command. Perhaps, in these places, we might glimpse the graviton.

The gravitational force field is extremely weak compared to the other three forces. Why is this so? This is part of the hierarchy problem, which can be stated most simply as: why is the weak force a million million million million times (1 with 24 zeros after it) stronger than gravity? This is another roadblock, making it difficult to combine the forces in a single mathematical formalism. One has to bridge this gap in strength, and not just a gap in the mathematical structures that underlays each successful theory of nature.

Experimental work and celestial observations continue to seek to tie the standard model to the cosmological behavior of galaxies, stars, black holes, and other physical objects. While the standard model contributes significantly to our understanding of the formation of matter-based structure after the big bang (after the first 10^{-11} seconds, which is roughly the period of time that can be recreated with present accelerator technology), it has failed to reveal what happened just immediately after the big bang before that moment (10^{-11} seconds) in time.

Historically, each time collider energy levels are improved, new particles are found. Since we do not know the more fundamental theory of the quantum realm beyond the standard model, we have no good guideposts telling us whether we can expect that trend to stop or to continue. Paralleling the quantum quandaries, there are many other questions in cosmology to be resolved. Dark energy and dark matter requires greater understanding.

The Roads to the Frontier

We are about to leave our comfortable inn on the road of the past and head into the frontier of human knowledge. There are many roads to choose from, many shadows that cloud our ability to choose the right way to fully describe nature and present a clear view to the horizon where answers await. It is wise to consider as many of the possibilities as one can, so we will endeavor to sample among many of these ideas in the remainder of the book, providing examples as we go, of places where ideas and methods intersect. Experimental tests may lie at those intersections.

In the late 1960s, members of the physics community, having reached a stumbling block in their search for a comprehensive understanding of the universe, sought other approaches to unifying the laws of the universe. Initially, a small number of researchers, continuing to search, returned again in the 1980s to something we'll soon explore in more detail, the "Kaluza-Klein theory," a concept that had lain dormant for almost thirty years. This return was primarily motivated by the curious discovery of a mathematical theory called "11-dimensional supergravity," a means to marry concepts in the standard model with those in gravity at the cost of adding more dimensions of space. It was felt that it held the mathematical potential for inspiring a new attempt to continue the conventional process of analysis, experimentation, and corroboration that is the hallmark of the physics research process.

Another group of physicists during the 1960s and 1970s worked on quantum physics, cosmology, black holes, worm holes (tunnels through space-time), the fundamental nature of space and time, as well as the Kaluza-Klein theory, and an even more bizarre extension called "superspace," as they sought the means to find a new thrust in physics research. It was this idea of superspace that led to the discovery of 11-dimensional supergravity.

These activities eventually morphed into something found in the depths of the equations that physicists were using—a new pathway called string theory. String theory is a significant departure from the now-conventional physics of the standard model. During the past forty years physicists have developed a multifaceted analytical framework, rooted in the original string theory ideas, to accommodate and build upon the results of twentieth century experimental work. The challenge to this work is that it continues to suffer from the inability to corroborate its results through experimental means.

Problems and questions about string theory will become apparent as we discuss this further. For example, the number of dimensions required to describe string theory is often described to be a number greater than the four dimensions of our universe (length, width, depth, and time).

While all of this was going on in the 1970s and 1980s, there were also efforts to independently develop a theory of nature based on a concept also tied to string theory: supersymmetry. This allowed for mysteries of the standard model to be explained using just the usual four dimensions, but at the cost of adding more particles to the universe. That being said, supersymmetry opened another door to another investigative pathway, a four-dimensional string theory that we will discuss later, that is being developed in fits and starts by a small band of dissident physicists (among them one of the authors, SJG).

Currently, physicists are contending with the surprises and conflicts presented by the data from colliders, satellites, and telescopes (across a broad spectrum of electromagnetic radiation), information that was obtained over the past few decades, that will multiply in size during the coming decades as experiments take in more data at a faster and faster rate given better instrumentation. This has caused many more questions to be asked than answers have been produced. The pace of technology poses an interesting challenge to the theoretical efforts that want to make sense of the cosmos. As in theory, a unified approach, bringing experimental and theoretical physicists closer together, may present the best chance of meeting this challenge of chasing the shadows away with the liberal use of a bright light.

Evidence suggests that quantum physics and cosmology must be unified to describe a comprehensive theory that will agree with what we observe. In a way, Isaac Newton set us on this scientific path by unifying what happens in the heavens with what happens on earth. The moon keeps in orbit around the earth for the same reason that the apple falls from the tree to the ground. That unification continued in the 1800s, with the brilliant work of the theoretical physicist James Clerk Maxwell, who united electricity and magnetism into a singular electromagnetic force. Einstein tried, in the last part of his life, to unify electromagnetism and gravity, but he did so in an intellectual shelter that ignored the discoveries of the quantum revolution he himself had helped to set in motion, the findings of nuclear forces and the zoo of new particles produced in particle accelerator experiments. The physicists of the 1950s and 1960s recognized that the electromagnetic and nuclear forces had things in common, and that the things that they held in common were more important than what divided those forces, so much so that it was possible to unify the electromagnetic and weak forces into a singular electroweak force. A grand unification of the electroweak and strong forces feels inevitable, although the path to it is not clear. A theory of everything, finally harmonizing the standard model and gravity, feels even more necessary, but has proven even more elusive.

By the conclusion of the twentieth century and continuing into the early twenty-first century, the physics community had analyzed and tested Einstein's general relativity, the modern description of gravity, and the standard model of quantum theory. These accomplishments separately achieve a comprehensive and accurate description of the world of both the large and the small. Together, they are well-developed descriptions of cosmology and quantum physics that yield a battle-tested (although perhaps incomplete) table of particles and interactions.

Large numbers of unanswered issues create a demand for new approaches to new directions. Gravity is so weak compared to the forces of the standard model. The known particles and forces have a pattern of mass, connected to the pattern of Higgs boson interaction strengths, whose ultimate cause is unknown. Dark Matter is totally absent from the standard model. Dark energy, if it's the energy of the vacuum of space, is grossly over-predicted by the standard model. The mathematics of general relativity is a square peg addressing the seeming round hole of the mathematics of the standard model.

How do we begin to cause any of these problems to unravel? We will now set off for the frontiers of human knowledge and, using the twin lights of theory and experiment, see what sense we can make of this universe. Get ready to leave the familiar (if strange) world that we know to enter realms of thought that can have stunning consequences for the nature of reality.

All research related to this idea was pretty much set aside. Indeed, for the next few decades, the majority of physicists let the idea of electromagnetic and gravitational unification wither as an unexplored idea. As physicists saw it, the classical physics of Newton's three laws along with Einstein's relativity was deemed sufficient to understand nature at scales greater than the level of the atom. Quantum theory and relativity took care of understanding things at the scale of the atom and smaller, so it was further built upon and seems to work just fine in four dimensions, demanding no more than that framework of space and time. Everything is under control, so who needs more dimensions?

Einstein described his vision of the universe—his geometrical description—as marble; smooth, and elegant. He sought to achieve a smooth solution to the theory of everything. He thought God would want an elegant solution that was simple and easy to understand, but this was not to be achieved in his lifetime.

Einstein likened quantum physics to wood—a crude, rough, incoherent mass of matter and forces that would forever remain a jumbled mess. This view was based on his inability to accept an approach that rested on a concept that uses a highly probabilistic approach to understand nature. He believed that we ought to be able to do better than that. But, because physicists generally followed Galileo's teaching that science must be based on observation, Einstein's wish for physics to move beyond the "wooden era" was thwarted.

Einstein wanted to define a theory of everything that was built on the foundation he first developed in 1916 in his theory of general relativity. No probabilistic nonsense would rear its head in *that* marble-like work. But this was not to happen, even after thirty years of pursuing this Holy Grail. It would be the probabilistic approach of the quantum, something he himself helped to start, that would be the path the field chose as the pennant to point toward progress. However, the Kaluza-Klein theory, "blessed" as it was by Einstein, remained lurking in the background in his world of marble that someone else would have to find. The Kaluza-Klein idea would later make a remarkable comeback.

The quantum path forward, chosen by many, completely embraced probability, leaving Einstein as a bystander to his beloved physics. Mathematical quantities, established by the ideas of Newton, represented particles that were replaced by new and different mathematical quantities that displayed the attributes of particles and the attributes of waves, depending on the circumstances of any given experimental observation. Newton's concept was based on the notion of particles that were envisioned as idealized billiard balls. Quantum theory would replace this notion with the idea of "the wave function." The pinnacle of this line of reasoning, reached in the middle 1970s, was the creation of the standard model of the elementary particles.

The Allure of Extra Dimensions

Are we really talking about dimensions? What are dimensions? Are they simply other directions in space? The theories of most interest in the present string theory community require up to eleven dimensions. The equations that have been developed with this method neatly unify the particles and forces in a way that the standard model cannot. The extra dimensions (or they might more appropriately be called extra directions) leave room (provide latitude) to incorporate the equations that are required to describe the forces and particles of nature, including gravity.

This framework, and that is the best way to describe what it is, while it can stand on its own (and, as you will see, provide its own unique and attractive features) can also be part of an even more complex theory of nature. We will come to string theory in more detail later, but it is sufficient to say now that the extra-dimensional framework will allow physicists to learn how strings work under various constructs. The ultimate goal of this is to make predictions about the natural world. As is common within the great cycle of science, if this framework can be pushed enough to make testable predictions about the familiar 3+1 dimensional world, then it may be possible to learn which is the correct model of nature and its dimensional content. Measurement can refine theory, and we can continue to probe deeper into reality.

Present measurements cannot demonstrate the credibility of an 11-dimensional construct, because, as noted by physicist Michio Kaku in his book *Hyperspace*, "theory projects that the unification of all forces occurs at the Planck energy, or about 10^{19} billion electron volts, which is about one quadrillion times larger than the energies currently available [in colliders today]." Further, the string, the proposed most fundamental quantity of physics, is so small that there is no instrument presently in existence that can observe it. However, other research suggests that extra dimensions may be large enough to be seen in future collider experiments at energy levels not much larger than presently available. We will discuss this later in this chapter.

The foundations of physics are based on observation, mathematical formulation, and experimentation. At present, the observation of and experimentation using string phenomena are not possible, but maybe we can lean a little closer to the infinitesimal world by finding ways to detect other dimensions of space.

Making Sense of Dimensions

From the observation of nature, there are three spatial dimensions (length, width, and height) and one time dimension. These have sufficed for the millennia during which humans have made measurements and observed behavior in the universe. It does not appear necessary from direct observational experiments that there needs to be more dimensions to be able to define the state of existence of a system or a process.

Do additional dimensions exist, and, if so, why are they not in evidence? This question has been pondered by many for years. Edwin A. Abbott (1838–1926), a teacher, author, and scholar, sought to make sense of dimensionality in a book

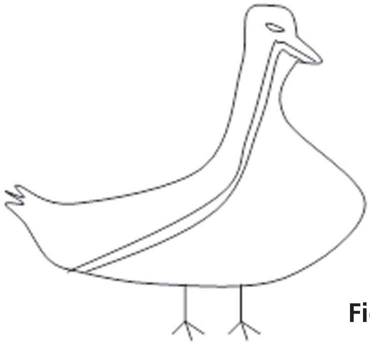

Figure 9.1 The Flatlander Duck

entitled *Flatland,* written in 1884. As far back as several centuries ago, mathematicians, physicists, and philosophers have manipulated dimensions in their investigations, dealing first with the three spatial dimensions to then add a fourth dimension, time. By the time physicists began to play with the number of dimensions in the early twentieth century, they were just the latest group to do so.

Let us consider concepts from Abbott's book to think about dimensions, and what it might mean to perceive of a *higher* dimension. Consider two-dimensional beings—Flatlanders—who live in a flat, two-dimensional world. The Flatlander duck (Figure 9.1) appears as it does in the illustration in this book. It lives on a flat plane. The duck can only recognize two-dimensional objects. When a three-dimensional object such as a beach ball enters its flat-surface world, the duck can see only a two-dimensional slice of it.

For example, see Figure 9.2. As the beach ball descends, the duck will observe a flat slice of the ball's shape growing uniformly wider and subsequently shrinking uniformly as the ball passes through the space between sky and ground. The illustration depicts the sequential size changes viewed as the beach ball descends onto Flatland. Each of its slices is seen as a circle, the diameter of which increases until it reaches the largest dimension at the equator of the beach ball. From there it diminishes in size as it describes its shape while descending to Flatland.

Figure 9.2 shows these sequential slices physically separated. However, the Flatlander would see a single disk growing from a small size to its largest size

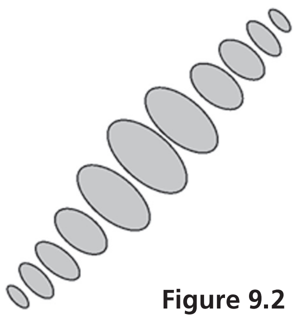

Figure 9.2 A Beach Ball Entering Flatland

as the ball reaches its equator. From there, the disk would shrink until it disappeared from view. This would be quite a stunning event to our Flatlander duck! Going about its day in its universe, it is witness to the sudden appearance of a disk that grows in size up to some maximum diameter, then shrinks again and vanishes. From the duck's perspective, something has come into existence out of nowhere, increased in size, then decreased in size, and disappeared into nowhere again!

Were a human, a three dimensional individual, to parachute to Flatland, the duck or any Flatland inhabitant would not see that third dimension - the person's height. The Flatlander would see only cross sections – tiny slices - of that person as he or she floats down to Flatland. An upright person (seen from beneath) would appear as cross-sections of the human body as if it was a series of still photographs from the bottoms of one's feet and ending at the top of one's head, the image changing shape as the body moves through the 2-dimensional space. First two oblong shapes followed by two circular shapes would appear as the person's feet and legs descended into Flatland, followed by various outlines of waist, shoulders, and head (ignoring the parachute).

Hold onto this image, and let's try to apply it (it will feel strange, we assure you) to our own 3-dimensional universe. Think now about what we would see viewing a five-dimensional object such as a *hypersphere*—a sphere in four, not three, dimensions—entering our four-dimensional universe. To us, trapped in our three spatial dimensions, it would seem as if a small ball appeared out of nowhere in front of us, growing in size to some maximum, then shrinking again until it disappeared. What a curious event that would be! A rash person would want to throw out the law of the conservation of energy during that moment, assuming it to be nonsense! Of course, no conservation laws will have been violated as there are now four spatial dimensions in operation. The hypersphere merely passes through our 3-dimensional slice of a 4-dimensional universe. You would not see the five dimensions of the hypersphere and would not be able to discern its true shape.

Thus, a 3-dimensional object is not perceived by the duck, or any other Flatlander, as anything but slivers of the whole. Portions of objects from a 3-dimensional universe might be sensed, but they would not be observable in their entirety. To us in our 3-dimensional universe, perhaps wrongly thinking that this is all there is to reality, we would experience a similar eerie and confused sensation were a higher-dimensional object to pass through our slice of the bigger space. This is how we can think about higher dimensions, and how we might experience them even if we cannot access them.

The Einstein Hypotenuse

We are not accustomed to dealing with dimensions beyond the usual three, so it appears that we cannot grasp the existence of more than three dimensions.

calculations, having more and more interaction complexity, remain finite and stable. The techniques that make that possible in the standard model apply here, and theoretical physicists long ago found that string theories, as mathematical frameworks, have lots of the "good behavior" that is cherished in the standard model.

Bosonic String Theory

Let us look at the early kind of string theory that was formulated right after Veneziano's work. It will help us to understand how physicists evolved the idea and, having dug deeper into the mathematics that describe it, confronted the first challenges to using string theory as a physical theory of reality. The first generation of string theory, initiated in part by the work of Susskind and Nambu, involved the bosonic string. That string was incapable of describing fermions, it could only work in a universe that had twenty-five spatial directions and, worst of all, it was mathematically inconsistent.

The bosonic string has two types of mathematical anomalies. These inconsistencies are subtle and it took a while to discover that these nonsense statements were buried beneath the complicated mathematics. Interestingly, one of these nonsense mathematical statements disappears when space has twenty-two more spatial directions than are apparent in the three of our universe.

Let us focus on the problem of many dimensions. The very first string theory, called "Type I bosonic string theory," was found to have the ability to make meaningful calculations only if the minimum number of dimensions in the universe was twenty-six: twenty-five in space and one in time. That many dimensions allowed for enough freedom in the theory to achieve the conditions for mathematical usefulness—at the cost of having to postulate more than eight times more spatial dimensions than are presently observed. A lessening of this problem was achieved by two of the most important tools that physicists have at their disposal: coffee breaks and chance meetings.

It was theoretical physicists John Schwarz and Michael Green who, in work conducted in the early 1980s, sought to eliminate the anomalies of the 26-dimension Type I string and many other anomalies that had crept into the mathematics of string theory during its initial stages of development. According to journalist Aida Edameriam in a *Manchester Guardian* article, physicists Michael Green and John Schwarz would not have collaborated and solved some of these problems had Schwarz not wandered into the CERN canteen in 1979 for a coffee break at a chance moment when Green was there. As a result of the serendipitous collaboration between Schwarz and Green, they reduced the number of dimensions required by the bosonic string. This and many advances accompanied the first string revolution in 1984. While their collaboration created a theory that nicely followed Einstein's gravitational theory with the emergence of a massless graviton on a closed string, it did more than that.

Capability, opportunity, time, and chance come together in unpredictable ways, and sometimes that is how theoretical physics makes advances. Brilliant breakthroughs cannot be ordered up on a regular schedule. Understanding the cosmos is not clockwork, predictable labor—it's messy, and if there is any lesson here it might be this: if you can't see your way through a problem, take a break—you might meet someone to help you see the problem in the right way.

Through this chance meeting in the CERN cafeteria, there began an intense dialogue addressing the most significant anomalies (i.e. the mathematical inconsistencies) of string theory—those of combining (unifying) matter particles (fermions) with forces (gauge bosons). They reduced the minimum number of space dimensions in string theory from twenty-five to ten.

The Tachyon Monster

But even given the mathematical assumption that there are now only ten or more distinct spatial directions, let's consider the second type of anomaly in the bosonic string. The second anomaly led to the prediction of a particle that was given the name "tachyon." The math paints the tachyon as similar to a Higgs boson particle, but with the curious feature that if one takes the square of its mass, one obtains a *negative number!* The only known solution to rid string theory of this problem is through the introduction of a new symmetry, one we have met before—supersymmetry.*

A theory that cannot describe fermions would not be able to describe our universe. Seeking to overcome this mathematical inconsistency in the bosonic string, physicists sought to include fermions by using supersymmetry. This led to even more string type theories and, eventually, to five superstring theories in all. The seeds that would enable understanding the landscape of string theory were planted much earlier, around the birth of string theory in 1971.

During 1970–71 Claud Lovelace discovered that the bosonic string is consistent with Einstein's special relativity with only twenty-five spatial dimensions. However, this theory has a class of problem, divergences, in which calculations run off uncontrollably. (The origins of this are unclear.) In the infinities of these mathematics, the tachyon of the bosonic string is revealed.

Shortly thereafter, Pierre Ramond added fermions to the model to create a two-dimensional supersymmetry. This had the effect of "taming the tachyon monster," making possible a full description of a supersymmetric string without need of the tachyon. Let's look more deeply at this monster and how it was quelled. In doing this, we will see the first intersections of ideas developed in

*The authors want to note that the concept of the tachyon has found its way into much science fiction over the past years and, in misunderstanding the nature and consequences of the tachyon, the phrase has become a kind of hollow techno-babble. (Nonetheless, it surely is entertaining for a physicist to encounter it, if not in its intended way!).

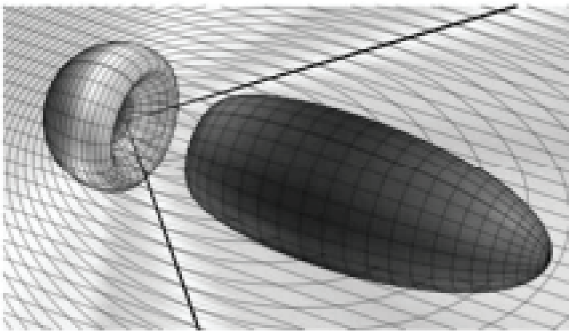

Figure 11.4 The Tachyon Monster

earlier chapters, and how their convergence leads us to a more reliable string theory.

But, for now, imagine a world where everything travels faster than the speed of light, where things are either very heavy or very light, and are unrecognizably different from the world we live in. Imagine the mathematics to be off the wall, that calamity happens all the time, and accidents of all sorts cause devastation. This is the world of the tachyon monster.

An artist's concept of what it might look like (were it to exist) is shown in Figure 11.4. It is a weird configuration, showing a leading shape with a wake behind it that is followed by a bullet-shaped object flying backward. The figure depicts the two-component object to be in motion, always at speeds greater than the speed of light. In special relativity, this would imply that it travels backward in time, violating the notions of cause and effect. Traveling faster than light has a similar effect in the universe because when traveling on Earth faster than sound, a shock-front develops. The first component in this visualization is a bow wake—a shock—shown on the left side of the figure. Because its speed is so great, the medium in which it is traveling forms a wake followed by an aft wake that looks like a bullet traveling backward.

Tachyons lead to other problems as well, such as defining what is probable. How would you answer the question, "What is the probability that something—*anything*—will happen today?" Because at least one thing happens every day—your cells divide, you take a breath, an apple falls from a tree, atoms jiggle somewhere—you would likely, and sensibly, reply one hundred percent. What would it mean to reply one hundred *and ten* percent. That doesn't make sense. You can't have more than all there is. You can't have more of a chance of something happening than *all* of the chances of that something happening. This, too, is an anomaly.

The tachyon, having faster-than-light speed and imaginary mass results in quantum mechanical probability calculations that violate totality and predict probabilities that exceed one hundred percent. This is a very disturbing situation—one that threatens the foundations of quantum mechanics. You can understand why this is a monster. The mathematics of strings, as a means to contemplate reality, is in jeopardy, unless the tachyon and other anomalies are eliminated.

Anomalies are nature's way of telling theoretical physicists that they have written elegant gobbledygook using her own beautiful language, mathematics. The real world has no numbers to identify measurable properties that imply imaginary mass. This was the downfall of the bosonic string as the correct idea to describe nature.

We earlier introduced the example of the Einstein hypotenuse to help you visualize invariant structures. The rest-mass of a subatomic particle is noted to be one such invariant. The tachyon monster can be thought of as having a hypotenuse whose final value, when squared, is a negative number. That is not possible in the real world! It was clear that something was wrong—not with the whole of the concept—just its mathematical workings. We have to capture this monster and tie it up.

The solution, it was found, could be achieved by referring to the spin properties of the particles described in the standard model. The bosons in the standard model all have integer-numbered spin (0 or 1). The fermions, however, have half-integer spin (½).

We referred earlier to the spin characteristics of bosons and fermions, but little was said of the property of spin except in reference to its rate. The bosonic string, the first generation string, was not able to interact with the electron and other matter particles. This is because until 1971, bosonic string mathematics had no way to produce those tonal vibrations that would create matter particles with their half-units of spin. This was the limitation of that first bosonic model, with its tachyon monster, making it clear that these problems had to be addressed.

To Spin a String

In 1971, three physicists—Andre Neveu, Pierre Ramond, and John Schwarz—brought a new slant to spin property and strings. Their innovation permitted the spin-rate of the electron (and all other fermions) to be incorporated into the mathematics that describes string characteristics. With this in place, matter particles could be included in the spectrum of string vibration modes. String theory was now deemed to have advanced from the first generation to its second generation. But, this still did not tie up the tachyon. More would need to be done to save string theory.

We've discussed quantum spin earlier. We have also discussed supersymmetry and developed independent notions of string theory in the early 1970s, which is a symmetry of space-time that unites the fermion and boson. When string theory incorporated supersymmetry into its mathematical framework, the monster was tamed. The anomalies that previously had appeared in the math—negative-mass, lowest-energy states of the theory—were canceled out may be measurable using today's technology or with technology to come in the near future. Supersymmetry is essential to the functioning of string theories. Perhaps the LHC will detect direct evidence for superpartners of the standard model particles. If so, this would certainly be a victory for the idea of supersymmetry; but, alas, it would not make the string theory picture any clearer, as SUSY is permitted to exist independent of string theory. Nonetheless, since string theory demands that supersymmetry must exist, it would bolster the cause of this means of unification of all forces in nature.

Based on these challenges, physicists are presently focused on those physical properties that are predicted by large extra dimensions (either within string theory or by employing alternative methods). That is the intent of the research that Randall, Sundrum, and many others undertook. The detection of extra dimensions at the LHC would provide a moment of relief for long-struggling string theorists, as string theory demands extra dimensions without giving a clear picture about how those dimensions would manifest themselves. Perhaps detecting something such as braneworlds will light the way! Still, it is important to keep in mind that the idea of extra dimensions came independently of string theory, decades before it was first conceived; evidence for extra dimensions is not definitive evidence for string theory.

Calabi-Yau Spaces

Let us look more closely at small, compactified extra dimensions represented by Calabi-Yau spaces. The mathematicians and physicists who worked with these objects realized that Calabi-Yau manifolds are more like coffee cups with handles than they are like spheres. A handle is attached to a cup leaving a hole through which one can place one's finger. For a very long time, mathematicians and scientists have known how to write equations describing an idealized coffee cup. Such equations describe holes in the surface configuration of a compactified space that can affect a string's vibration pattern. It is easy to expect that the vibrational pattern of a ceramic ball, when it is struck, will be very different from that of a teacup being struck, even if the two are made from exactly the same mass and volume of ceramic material. This concept implies that the form a manifold takes will affect a string's performance, and the mathematics confirms this intuition. Figure 12.6 depicts such surfaces. An arrangement of Calabi-Yau spaces located at each point in a 3-dimensional space is shown. These small surfaces determine the force structure of the space while they do not disturb its four-dimensional behavior. The question is, does this concept work?

Two dimensions of the three-dimensional universe are shown by the illustration—plus, at each point in this two-dimensional picture there is a six-dimensional Calabi-Yau manifold compactified to a very small surface. The third dimension can be assumed to be perpendicular to these two dimensions such

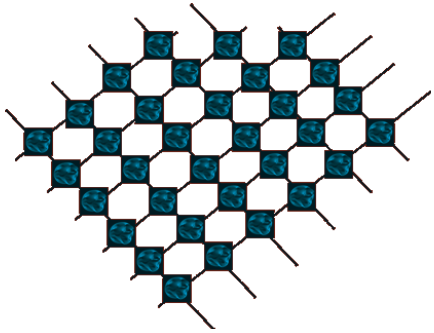

Figure 12.6: 3-Dimensional Space Using Compactified Calabi-Yau Manifolds

that it comes out of the page. The third dimension would contain an identical configuration of surfaces. This structure goes much of the way toward answering one of particle physicists' most intriguing questions: why are there three families of elementary particles—up/down quarks (electron and electron-neutrino), charm/strange quarks (muon and muon-neutrino), and top/bottom quarks (tau and tau-neutrino)? Why not one, or four, or any other number? The answer proposed by string theorists follows.

The universe, as viewed by an observer, would behave as though it had only four dimensions. The low-energy behavior of the higher dimensions would not be observed due to the inability to sense them. Nonetheless, the properties of the Calabi-Yau manifold have important implications for low-energy physics. The types of particles observed, their masses, quantum numbers, and the number of generations, constitute some of these properties. A major problem has been that there are many types of Calabi-Yau manifolds (thousands upon thousands) and no way to know which is the correct one to use. The mathematics of superstring theory began by describing a universe with ten-dimensional space-time (one time-like direction and nine space-like directions). By assuming that the shape of the extra directions are mathematically similar to surfaces like coffee cups possessing handles, string theory was found to possess the possibilities for a four-dimensional representation of physics.

A long-standing hope of string theorists is that a detailed knowledge of full superstring theory (M-theory, the underlying framework that leads to the known superstring theories) will provide an explanation of how and why the universe flowed from the ten-dimensional physics thought to exist during the high energy phase of the Big Bang, to the low energy four-dimensional physics that is observed today. This is a rich area of exploration in modern string theory. Can there be a singular, unique Calabi-Yau manifold that makes this work? Maybe there is a mathematical theory or framework that shows how all possible Calabi-Yau manifolds are related to each other in some simple way—so that it doesn't matter which one is chosen.

Or, maybe the notion of requiring extra dimensions is the problem in the first place. This is where some dissidence crops up. While supersymmetry plays nicely with ten-dimensional superstring theory, one of the authors of this book (SJG) proposes that supersymmetry also enables the possibility for four-dimensional, not extra-dimensional, string theory.

The Dance of Theory and Experiment

Theory and experiment in physics go hand-in-hand. The latter prevents the former from being a branch of philosophy (from which physics sprang as it evolved through the proofs provided by experimentation). Experiments confirm to physicists the real-world behavior of particles and forces. Using string theory, physicists employ mathematics to explore objects so tiny that experimentation is currently unable to test for their existence; so tiny that naively scaling present accelerator technology, one would require a collider that is at least the size of the Milky Way galaxy to detect them.

Physicists, instead of seeking to prove such small dimensions, are now focusing on those physical properties that are shown by string theory to be within the current range of experimentation. In his book, *The Elegant Universe*, Brian Greene presents his viewpoint on experimentation. He relates that many physicists believe that it is important to use experimentation as a means to underpin string theory. Such activity would strengthen the confidence that their achievements have merit and that their pathway is focused. This has been the way science has always worked. Through trial and error, experimental physicists have moved theoretical work along, demonstrating the detailed behaviors of particles and forces by using scientific approach to observe and explain investigated phenomena. Historically, theory has evolved from practical demonstration or it has been driven extinct.

Some now argue, according to Greene, that this may be the time for theoretical work to take the lead in defining theory so that experiments can be developed to assess the theoretical claims. This takes progress out of the realm of intuition into a mode in which it steers experimentation to yield indisputable outcomes. If not, we may continue to move haphazardly into an abyss of uncertainty. The result would be to achieve solutions in a more efficient manner; targeting with a rifle rather than shot-gunning.

To a degree not generally perceived by non-physicists, the reversal of the roles of theory and experiment *has* been occurring for a few decades. Almost all major discoveries in particle theory since the 1960s have had mathematical avatars that came before the actual discovery. The charm quark, first observed in 1974, is often described to have been a surprise discovery, except that physicists Sheldon Glashow, John Iliopoulis, and Luciano Miani had argued in 1970 that such a quark had to exist. It was found four years later. The recent detection of the Higgs boson is another example of a discovery preceded by the mathematical framework that predicted it.

star's own gravitational force would capture its own light! This is a remarkable insight given that Newton's *Principia* was written just ninety-six years earlier and Einstein's theory of general relativity would be completed one-hundred and thirty-three years after Michell's suggestion. Michell had conceived of "dark stars," an intellectual first given the then-recent foundation of the laws of mechanics. He also the fathered the idea of the binary star, a system that played a key role in the discovery of the accelerated expansion of the cosmos and plays an equally key role in a subject to be discussed later in this chapter, the collision of two black holes. Michell was a remarkable thinker.

An understanding of black holes lies at the intersection of cosmological and quantum theories, an understanding that did not arise without a struggle. When the quantum mechanics of black hole behavior was being developed, serious contradictions appeared. A black hole must be described by accounting for the behavior of both its singularity, the remnants of a dead star at its heart, and its event horizon, a virtual surface we perceive of as surrounding the black hole, beneath which surface even light, the fastest thing in the cosmos, cannot escape the singularity.

During the 1970s, many physicists researched and portrayed the black hole and the physics surrounding its behavior. We'll meet some of them, including one notable physicist, Stephen Hawking. Among other findings, Hawking's studies showed that, unexpectedly, energy could radiate from a black hole, developing an equation defining the temperature at which this radiation would occur.

The Black Hole Connection

Black holes are very mysterious celestial objects. We are just beginning to understand what they are and how they work.

It was Karl Schwarzschild (1873-1916), an astronomer and physicist, who first solved Einstein's equations for the case of a star collapsing to a very small radius, and thus preventing its light from escaping its own gravitational field. Schwarzschild's short life of forty-three years was filled with many accolades and accomplishments. He wrote his first two papers on celestial mechanics at the age of sixteen. He defined the Schwarzschild radius, the radius below which, if a body of mass, M, is shrunk, the ensuing warping of space-time became so extreme that not even light could escape. This radius is given by the equation:

$$r_S = 2GM/c^2$$

where r_s is the Schwarzschild radius, c is the speed of light, G is Newton's gravitational constant, and M is the mass of the body.

For instance, our sun has a Schwarzchild radius of 3 km. If one were to make our star into a black hole, its present radius of 700,000 km would have to be compressed inside of a sphere having a radius of 3 km. The sun is expected to end its days as a white dwarf star, having a radius of about 1% of its current size, or about 7.000 km. This is still very safely above the Schwarzchild radius; so exhale, the earth will not fall into a black hole.

The Schwarzchild radius also marks a black hole's event horizon. Much like the horizon at sea, an event horizon is the illusion of a boundary caused by curvature. The earth curves away in the distance causing the ocean to appear to end at some distant point. It is why sailors in the past feared sailing off of the edge of the world, even though the earth has been known to be round for almost 2,500 years. Similarly, space-time around a black hole is curved such that there is a point beyond which light can no longer escape, creating an event horizon and the illusion that there is an "end" to space (and time) at that location. For now, no event that occurs inside an event horizon can be known to people outside an event horizon.

Stars are born, they live for a while, they die, and, if conditions are right, they leave a black hole behind. However, there is another potential source of the creation of black holes; the big bang itself. Shortly after the big bang, the conditions were ripe for the creation of black holes. These are called primordial black holes to distinguish them from those that arise from the deaths of stars. Primordial black holes, together with dark matter, must have been the anchors for galaxy formation preparatory to the first generation of stars that began to shine with their own light.

The formation of a black hole depends on both the mass of and the radius of the star. After much searching of the heavens, a body of data has been compiled that suggests that black holes can be found in many places—in interstellar space, for sure, and at the centers of galaxies. This last statement may be true for *all* galaxies.

Black holes may be to galaxies what plate tectonics is to continents. The continents of earth are anchored to "plates," whose relative motion is a cause of earthquakes. It seems possible that galaxies are similarly anchored to black holes. Our own Milky Way galaxy possesses such a black hole "plate" called Sagittarius A* (pronounced "Sagittarius A-star"). It possesses the mass of about four million suns.

But the supermassive black hole at the center of our own galaxy is neither the only, nor the first, black hole of which humans became aware. The very first black hole candidate was catalogued in 1964, but only later (in 1971) was it realized to be a candidate for a black hole. Decades of experimental work was required to fully satisfy the scientific community that this was definitively a black hole, but by the 1990s this was well established. Let's look more closely at the black hole called "Cygnus X-1," to help understand how one can detect an object from which no light can escape.

Cygnus X-1 is an x-ray-emitting object in the constellation Cygnus, the swan. Earlier, we mentioned binary stars, partner stars that dance around each other for hundreds of millions, or even billions, of years. Cygnus X-1 is part of a binary system. The partner star, named HDE 226868 is visible. It is a blue supergiant star. Blue supergiants are at the top of the stellar "Main Sequence," a nomenclature plot of brightness and color. This type of star lives fast and dies young as they deplete their hydrogen core quickly and move to a late stage of hydrogen fusion causing them to become supergiants. HDE 226868 is about 400,000 times brighter and has a mass about twenty-five times our sun. She is probably only a few million years old. When HDE 226868 was born from a condensing cloud of interstellar hydrogen gas, the first modern humans had probably only just parted ways with our upright-walking ape cousins.

HDE 226868 is seen to "dance" with its partner. Measurements of this dance have concluded that it takes about 5.6 days to complete one mutual revolution. Compare that to the earth, which requires 365.25 days to complete one revolution with our dance partner, the sun! Factor into this calculation that HDE 226868 has a mass that is almost eight million times greater than that of the earth. What fearsome gravitational partner could make a supergiant blue star dance so quickly while locked in the strong embrace of its gravity?

If you look with your eyes, you cannot see an answer to this question, as no visible light comes from the partner. How strange! If one uses the measured information about HDE 226868 to estimate the mass of its partner, one concludes the mass to be about fifteen times that of the sun. We know many stars with masses in that range. They shine brightly in the sky and are easily seen with the naked eye. However, no instrument to aid the eye will reveal HDE 226868's unseen partner.

It was the detection of Cygnus X-1 using x-ray light that provided the first evidence of its existence. The partner star, HDE 226868, was established as its partner much later than that. From careful measurement we know that the pair lies about 6,070 light-years from Earth. We presently see this system as it existed 6,070 years ago, when its visible light and the x-rays we observe today began to move toward us on their long journey.

Cygnus X-1 was the first object to qualify as an excellent candidate for being a black hole. Its mass is huge, yet it is invisible to the naked eye while it emits x-rays. This is the same way we know that there is a black hole at the center of our own galaxy, Sagittarius A*. We know this not by direct observation, but because we can see stars very close to it that cycle at incredible speed around nothing that appears to be there.

But how do we know that the unseen partner in Cygnus X-1 is a black hole? To comprehend that, we need to know the proper conditions for the formation of a black hole. The conditions for the collapse of a shining star to a black hole is called Chandrasekhar's Limit, named after Subrahmanyan Chandrasekhar (1910–1995). Chandrasekhar was born in Lahore in British India, before it was partitioned into India and Pakistan. He earned his Ph.D. in 1933 from Trinity College at the University of Cambridge and is famous for his ground-breaking work in the evolution of stars.

Chandrasekhar discovered an important limit in the mass of a star. While he was not the first to do so, his work was independent and far more precise than the work that had preceded his. He was only nineteen years old.

In 1935, just after earning his Ph.D. and seeking to have his results accepted by the scientific community, he found himself in contentious disagreement with the world's then-most eminent cosmologist, Sir Arthur Eddington. The Chandrasekhar limit he proposed was a statement about the maximum extent in mass and radius that can be possessed by a white dwarf star. Chandrasekhar argued that stars above this limit (1.4 times the mass of the sun) would collapse in runaway fashion to a black hole. Eddington, while he was certainly aware of the possibility for black holes to exist, rejected this idea and, being such a force of authority, many listened to him. But Chandrasekhar's argument was ultimately seen to be correct.

In further investigations over time, we now know that this limit is not the limit at which a star will collapse to a black hole. The further development of quantum mechanics revealed that the nuclear matter in the collapsing core must first almost entirely convert to neutrons, forming a neutron star. Because neutrons are fermions, and fermions are forbidden by their spin-1/2 nature to occupy the same point in space together, they resist further collapse *unless* the stellar core is about three times the mass of the sun. Physicist Robert Oppenheimer, and others, using the concepts that Chandrasekhar had developed, combined with the state-of-the-art quantum physics of 1939, refined this picture and found that this slightly higher mass was one at which collapse is unstoppable. Even the fermion nature of neutrons is not enough to save this dying star. Stars above the Chandrasehkar limit will result in a neutron star. Stars above the Tolman-Oppenheimer-Volkoff (TOV) limit (a limit on neutron stars analogous to Chandrasekhar's white dwarf limit) will form a black hole. You can see why Cygnus X-1 is an excellent candidate to qualify as a black hole—it possesses a mass about five times above the TOV Limit.

A black hole is a highly compressed state of subatomic matter. The location in space where the original matter resulting from the death of a star resides is known as the singularity of that black hole. It is predicted to occupy a volume smaller than the nucleus of an atom. It was John Michell, with all of his imagination and armed with the power of Newton's mechanics, who conceived of dark stars larger than our own sun and having the immense gravity necessary to stop its own light from escaping. General relativity and quantum mechanics go further, to allow for something far, far stranger. A black hole is truly a dark atom, one whose mass is greater than our sun but whose size is smaller than the nucleus of a single typical atom. Where typical atoms reveal their presence by emitting light, black holes do not.

We see why a unified field theory becomes a necessary tool for probing the universe. If we are ever to fully understand the black hole (and the birth of the universe), we need a framework that comfortably marries gravity and the quantum realm.

Some Things Black Holes Do

Black holes are like the beast, Charybdis, of Greek myth. This ship-eating whirlpool, depicted in Homer's *The Odyssey*, was a danger that Odysseus, the protagonist, was forced to sail near to if he was to continue his heroic journey. Charybdis didn't come to him, Odysseus had to go to it. The danger of a black hole to matter is not that a black hole encounters matter because collisions between stars, alive or dead, are rare. Rather, it is when matter comes to a black hole that things get strange.

Because a black hole is an extreme warping of space-time, space and time behave oddly as one draws near to a black hole. Time runs slower and slower as objects come closer and closer to the singularity. Because time measurements are relative to something, by slower we mean slower relative to the clocks held by an observer far from the black hole. Space-time is so stretched that time is stretched, too. While people close to a black hole do not notice this effect, far away observers will perceive astronauts who are growing closer to the singularity to move more and more slowly as they approach it.

While this may sound inexplicable to you, this effect is present in our everyday lives. If you have a mobile device with you, take it out. Does it have the ability to locate your position on the earth using GPS, the Global Positioning System? If so, choose an app that has a map that shows your location. That a GPS device linked to the GPS system can so accurately place you as a marker on a street map is thanks to time dilation. How is this done?

You and your phone are standing in a place on the surface of the earth. The satellites that calculate GPS location information are orbiting the earth twice a day far above you, about 20,000 kilometers (almost 12,500 miles) from the earth's surface. The earth's gravitational field at the surface is much stronger than it is 20,000 km from the surface. As a result, time runs ever-so-slightly more slowly down here than it does when compared to the orbit. Astronauts do not notice this effect, but the atomic clocks on GPS satellites can!

This effect must be corrected for. If not, the clocks on the GPS satellites will, more and more, lose synchronicity with their twin clocks on earth. This would result in your position becoming more and more inaccurate each day! Software and hardware are designed to correct for this, keeping the GPS system accurate. Without these general relativistic corrections, the GPS system would misplace positions by about 10–11km (about 6 miles) during the course of a day.

Let's look at some other aspects of black holes. They are often accompanied by a halo of ordinary stars and other matter (such as gas) that orbits them just as planets and asteroids orbit our sun. This halo-like structure is called the "accretion disk," but, unlike our solar system, their activities can be violent and chaotic. Sometimes material of the accretion disk crosses the event horizon and is sucked into the singularity. For now, we cannot know what happens to matter space-time, traveling at the speed of light, finally reached our planet, 1.3 billion years after the event had occurred.

When this discovery, named GW150914, was announced on February 11, 2016 (it took that long to process and verify the data), the scientific and popular press was taken by storm. For the first time, humans had put an ear against the floor of the cosmos—space-time itself—and heard the thud of distant giants tumbling around in the dark. For the first time, we had received information that may have come straight from the event horizons of two black holes. In just one day, an entirely new form of astronomy—gravitational wave astronomy—burst into existence. What Galileo Galilei did for the world in creating astronomy by turning a telescope to the night sky, LIGO has done for us by turning our ears to space-time to listen for the distant messages of cataclysmic events.

The LIGO scientific collaboration announced a second detection on June 15, 2016. This second event had occurred months earlier, on December 26, 2015. Again, careful analysis was done to rule out alternative hypotheses. The conclusion was that this was yet another black hole merger, named GW151226. This merger involved lower-mass black holes, approximately fourteen and seven solar masses, but definitive nonetheless. The occurrence of binary black hole mergers may be common in the universe, and if they are, LIGO expects that it will detect hundreds of them per year as the collaboration continues to upgrade and develop its instrumentation. Other instruments like Virgo, GEO 600, and TAMA 300 should expand the sensitivity of these searches, allowing for the creation of a global-scale gravitational wave observation network. The entire earth will be tuned in and listening for these events.

Wrap Up

Black holes are the result of a stellar remnant of mass in excess of three times that of our sun, where the runaway gravitational collapse of a star cannot be stopped by known quantum effects resulting in a singularity that strongly warps space-time around it—a black hole. Physicists like Schwarzchild, Chandrasehkar, and Oppenheimer had early-on described the conditions of this phenomenon. The discovery and subsequent characterization of Cygnus X-1 gave us tools to better understand how to measure black holes using material outside their event horizons—the point of no return beyond which no information escapes the black hole.

However, as Bekenstein and Hawking conjectured in the 1970s, perhaps information does escape the event horizon of a black hole in the form of Hawking radiation. Further, the physical scale of the black hole, its mass, and the surface area of its event horizon, might define the thermodynamic properties of the black hole, its temperature, and entropy. But in doing so, Hawking suggested that this might doom information that enters a black hole. This led to a paradox in the laws of physics that theorists like Hawking, Susskind, and 'tHooft have been struggling to understand by using tools like superstring theory and extra dimensions.

These efforts have led to the suggestion that a black hole—and perhaps our entire universe—can be understood by the information encoded in quantum states on the surface of the black hole. This holographic principle tells us that the higher-dimensional space of a black hole might be summarized entirely by the state of its event horizon, a 2-dimensional surface. This leads to an intriguing set of new ideas about relating higher-dimensional space-time models to lower-dimensional field theories (the AdS/CFT correspondence). Perhaps, in thinking about the black hole, physicists have discovered a means to resolve the problem of dimensionality in superstring theory and M-theory.

Data, however, might be nipping at the heels of these ideas. For the first time, physicists have detected gravitational waves by observing colliding black holes. We may now have access, via gravitational wave chirps in space-time, to information from that mysterious boundary of the black hole, its event horizon.

Chapter 14

What is a Universe?

When you think about the whole of existence; i.e., the "universe," what comes to mind? Some people think about the fields or the forests that lie at the town line. To them, the whole of the meaningful world may lie within those lines, the borders of a town in which they may have spent their entire lives. To others, the whole of existence may be the few city blocks of their neighborhood, just sufficient to describe where they live and work and shop and play. The whole of existence can be intensely personal, for it is these personal things that occupy our daily thought and interest and help to make our lives worth living. There are still others who are more global in their thinking and consider the Earth, with its diversity of land, people, resources, and ideas to be their universe. Still others reach for the stars, some in reality, most in their imagination, and want to understand where they really are in the cosmos. To them, the universe is more than just an earth that circles a mid-sized main sequence star—it is all the planets, all the stars, all the galaxies, and all the spaces between these things that are the universe.

When Nicolas Copernicus (1473–1543) advanced the idea that the earth is a planet circling around the sun, this was, indeed, a rethinking of what it meant to consider the whole of existence. Accepting this idea meant, to many, that we were not in a *special,* privileged place. This idea, however, also places us in a grander universe, one where we and other planets dance in endless orbits around a central star, worlds waiting to be explored.

When Edwin Hubble (1889–1953) provided evidence that there are stars located beyond our own Milky Way galaxy, in what appeared to be *other* galaxies, it truly boggled minds. We now know that our universe has more than one-hundred billion galaxies. This is an awesome and stunning revelation! Rather than interpreting this in a way that makes us feel less special, let us instead interpret this humbling revelation to be confirming of just how special it is that a species like our own, trapped on the surface of a small planet around a mid-sized star, has come so far in understanding how vast the universe truly is.

But even more wonders exist in the understanding of our place in the universe. The Milky Way galaxy is but one of fifty-four or so galaxies known as "The Local Group." There is a similar but much larger cluster of galaxies called the "Virgo Cluster" nearby. For a long time it was assumed that our local group was part of the Virgo Cluster. However, it was recently realized that our local group is part of an immense "supercluster" containing at least one hundred galaxy clusters, each composed of hundreds or thousands of galaxies.

So, how do we know that our local group is not part of the Virgo Cluster? One way to know whether a planet or a planetary-like object is part of a solar system is to determine whether it orbits a sun. We can resolve this question about the trajectory that our local group follows. It turns out that the answer is that the local group is moving toward a region of space called the "great attractor." Our local group is just one of thousands of such galaxies moving toward the great attractor. The great attractor is to galactic clusters as the sun is to planetary objects in the solar system. If you happen to think that this is the biggest structure in the universe, it's not.

The Virgo Supercluster is but one lobe of an even greater structure, a cluster of superclusters. This immense structure, home to 100,000 galaxies, has been given the lovely sounding name, "Laniakea Supercluster," derived from the Hawaiian phrase for "immense heaven."

Long before we knew about superclusters, or clusters, or began to understand galaxies, one of the minds working hard to understand the early work of finding our location in the universe belonged to Albert Einstein. In 1916 he completed the theoretical magnum opus that he had worked on since 1907, the general theory of relativity that we discussed earlier. After completing it, Einstein realized that these equations could be used to describe the history of the entire physical universe. At that time, the world's most respected cosmologists thought the universe was static and eternal. In order to get his equations to agree with this commonly held belief, Einstein had to introduce a new term into his equation. He needed, he thought, only to put in a constant which he named the "cosmological constant" and the toy universe he imagined in general relativity would match what "everyone knew was true"—that the universe was static and unchanging, neither growing larger nor growing smaller. Today, we would say that he had added a "fudge factor" to his equations. It turns out that the conventional wisdom motivating his choice was wrong.

So, after 1929, when Hubble showed that the universe was expanding, Einstein had to go back and erase the fudge factor, calling it the biggest blunder of his career. While we know from observational evidence that, in fact, the universe grows larger over time, there may still be a need for a cosmological constant—one that, rather than hold everything still in the cosmos, makes it grow larger over time at a faster and faster rate.

The earlier chapters of this book describe aspects of the universe as its fundamental building blocks—the forces that bind together those building blocks; the ideas of quantum physics and space-time that are the basis of successful explanatory frameworks for matter and forces, including the standard model and general relativity; and the speculative ideas that attempt to unite all known matter and forces under a single theory of nature, such as supersymmetry,

Chapter 15

What the Heck's the Higgs? —Part II

In the first part of this book we explored the history of science and, specifically, physics and astronomy. We looked at the cosmic and the subatomic realms. We came to see how conditions within the standard model pointed the way to the discovery of the Higgs particle. We explored the consequences of the standard model, and found that, while it has had much success, it leaves a number of important questions unanswered. In addition, it fails to explain a number of important observations. What is the nature of dark matter? Why is the cosmos experiencing accelerated expansion? Here the standard model either falls silent or, worse yet, offers nonsensical answers.

We have met the Higgs boson. We learned something of the story of its conception, the struggle for this idea to be tested, and the eventual success of the model as an explanation for the origin of fundamental mass. We struggled with supersymmetry and extra dimensions, owing to untestable string theory, and we introduced the idea of a system-modelling approach to help understand how these "components" might work in our universe. You might feel as though this is the end of a great story. However, as we will explore in this chapter, the discovery of the Higgs and the confirmation of its role in nature is but the opening chapter of a much larger narrative *and*—this story is full of peril and mystery!

We will see how the Higgs boson is incapable of explaining all of the mass that is present in the standard model. We will see how the measured mass of the Higgs boson suggests that we live in a universe set on the edge of a precipice that threatens, one day, perhaps, to end our existence. We will see how the Higgs mechanism connects to ideas beyond the standard model: extra dimensions; supersymmetry; and superstring theory. While exploring this newest frontier, the Higgs boson, we will grapple with a most engaging question: *What the Heck's the Higgs?*

The Little Ghosts

The Higgs boson, and its associated Brout-Englert-Higgs-Guralnik-Hagen-Kibble mechanism for realizing fundamental mass in a quantum field theory, is the secret to how particles acquire mass. Or is it? It seems to work exceptionally well for the electroweak bosons—the photon, and the W, and Z bosons. Early evidence suggests that it also explains the origin of mass for quarks and the electrically charged leptons (electron, muon, and tau), but there is another place in the standard model where mass has been found— a place where it was not expected to be. This turns out to be a sticky bit of the standard model, one that continues to vex theoretical physicists. Neutrinos, the little cousins of the electron, muon, and tau, also have mass . . . and it seems that the Higgs boson may have nothing at all to do with this.

To understand why this may be, we have to jump back in time to the time of the origins of the idea of the existence of a neutrino. The story begins during the same booming era in which the atom was being thoroughly scrutinized, the 1920s. The quantum theory was under development. Einstein had already wowed the physics community and the world with his theories of relativity.

Radioactive decay had been discovered in the late 1800s, and, in 1899, Ernest Rutherford (1871–1937), who would go on to discover the nucleus of the atom and the proton, was studying this newly discovered strange phenomenon. Seemingly without any prompting from an external entity, atoms would spontaneously emit energy. Rutherford classified the then-known kinds of radiation into two categories: alpha and beta radiation, named for the first two letters of the Greek alphabet.

It will be beta radiation that concerns us here. Beta radiation is distinguished by the fact that the radiated energy is carried by a specific subatomic particle. Research revealed that this particle was the electron, discovered by J. J. Thomson (1856–1940) in 1897. The electron that emitted beta radiation was no ordinary electron—it moved very fast and carried tremendous energy as a result. Beta radiation—fast electrons—will penetrate through millimeters of aluminum metal. It was Henri Becquerel (1852–1908), the discoverer of radioactivity, who found that beta radiation was the same as Thomson's then-recently discovered particle, the electron. In 1901, Ernest Rutherford and Frederick Soddy (1877–1956) learned that beta radiation was accompanied by atoms that changed their type, something that we later came to understand was a nuclear process—changing the number of protons in an atom.

When two physicists, Lise Meitner (1878–1968) and Otto Hahn (1879–1968), measured the energy spectrum of beta radiation in 1911, a real mystery began to take shape. Unlike other kinds of radiation (e.g., alpha radiation), in which the emitted particles carry very regular and specific energies every time they are emitted, beta radiation particles appear to carry a smoothly varying amount of energy, even when emitted from different atoms of the same atomic element!

A beta particle emitted from one atom could have a given energy level, while a beta particle emitted from an identical neighboring atom carried a different level. What could explain this unusual phenomenon?

Many other mysteries abounded about beta radiation, including the conservation of spin angular momentum in nuclear transmutations. In 1930, after decades of study of beta radiation and much theoretical labor to understand the problem, a physicist, Wolfgang Pauli (1900–1958) wrote a famous letter stating his speculation about the cause. Unable to attend a meeting of the Physical Institute at ETH Zurich, he wrote in a letter to the participants that he had hit upon a "desperate remedy" to the problem involving the prediction of a new and never-before-observed particle that he called the "neutron." Too afraid to publish this "desperate remedy," he sought input from his colleagues and provided his thoughts in the letter.

The particle we today call the neutron was discovered by James Chadwick in 1932 and he named it using the same word as had Pauli. But this constituent of the nucleus was later determined to be too heavy to explain Pauli's vision of neutrons. The physicist Enrico Fermi (1901–1954) renamed Pauli's hypothesis "neutrinos" (Italian for "little neutral one") so that they would remain a distinct category of as-yet-undiscovered (and possibly non-existent) particles.

The reason that this idea was not taken seriously was that the neutrino, if real, was so elusive as to be potentially undetectable. Fermi was the first to develop a theory of beta decay, attributing the emission of the beta particle to the following reaction, the decay of the newly discovered neutron (n^0):

$$n^0 \rightarrow p^+ \, e^- \, \nu$$

where p^+ is the proton, with its positive elementary charge, e^- is the electron, with its negative elementary charge, and ν (the Greek letter, pronounced "noo") is the neutrino, having a proposed zero electric charge. We can read the above equation like a sentence that tells us about a physical process in nature: The neutron (n) decays (the arrow) to a proton (p), electron (e), and neutrino (nu). Fermi's work appeared in 1934 and represented a kind of unification: the unification of the neutrino hypothesis with Paul Dirac's postulation of the anti-matter electron, the positron (which was, itself, only relatively recently discovered, in 1932). By putting it in a clear framework, Fermi had set the stage for making predictions. However, in an ironic twist, his paper was rejected from the most prestigious journal of the day, so he published it in an alternative journal. The idea did not immediately catch on (even though it turned out to be correct), so Fermi decided to switch from the pursuit of theoretical physics to experimental physics. This was likely a setback for theoretical physics but a huge gain for experimental physics.

The neutrino was predicted to be discoverable by inverting the neutron decay reaction by moving particles around in the equation. The rule is that when mental forces in nature than the electroweak, strong, and gravitational forces, then perhaps we've missed an important method for understanding dark matter.

Theoretical physicists have been considering these possibilities for a long time, and what has emerged from that are ideas about a "dark sector" of the universe. Perhaps there is a kind of "dark standard model," a shadow of the known standard model, with ways of bridging between the standard model particles and the dark sector particles that could be probed by particle colliders such as the LHC.

Indeed, LHC experiments have been searching for evidence that the Higgs decays to invisible final states, as mentioned earlier during the discussion of neutrinos and mass. If the Higgs is observed to readily decay to undetectable final states, perhaps it is explained, not by neutrinos, but by something else. It might be connected to dark matter!

Perhaps the dark matter mass is such that the Higgs can decay to a pair of these particles. This is something that fits nicely into these dark sector ideas. Searches have been conducted at the ATLAS, CMS, and other experiments for evidence of such dark sector aspects of the Higgs interaction. No compelling evidence has been found in favor of these ideas, but it is still quite early in the LHC program and experimental and theoretical physicists will continue to improve the techniques for searching for dark sector physics. After all, if dark matter was easy to detect, it would have been detected long ago. Indeed, all experiments—direct searches and the LHC alike—expect that dark matter will first be detected at the edge of sensitivity before being revealed in greater detail, with subsequent measurements.

Thus, perhaps, the Higgs may be a pathway to understanding dark matter. The efforts we have described here, and many others, are under way to assess this idea. Because the Higgs has such an intimate connection to mass, there is a belief that the Higgs and dark matter might play a fundamental role together. However, this idea may not be true and the light of experiment continues to probe the dark corners of the cosmos to see what is true about dark matter and what is not. The Higgs might serve as a sign post on the road into the frontier, but its utility is still not entirely clear.

Wrap Up

Okay then! What the heck's the Higgs?

It is a spin-0 particle whose quantum field, and thus quantum potential, defines the foundation of the electroweak theory. Its pattern of interaction with other quantum fields and particles yields the masses we observe in nature. But, what sets the pattern in the first place? The standard model, while describing the properties of this particle quite clearly, is mum on one of the most fundamental questions about the structure of the universe.

The Higgs may be more than just a means to understand the mass of quarks, gauge bosons, and charged leptons in the standard model. Can it shed light on the new mysteries associated with neutrino mass? What is it that sets neutrino masses to be *so much smaller* than even the smallest mass known before, the mass of the electron? Why would nature want things this way? Again, the standard model is mute. But, perhaps the Higgs boson can provide a means to see forward in this question, paralleling the tremendous efforts of dedicated neutrino experiments to shed more and more light on the properties and behavior of the neutrinos.

What is the fate of our universe? Will matter and the forces as we know them continue to gently evolve the universe for billions of years into the future? Or, might the Higgs mass serve as a warning that the universe has not quite settled on its foundations yet? If so, there is a small chance that, at some point in the future, the universe might quantum tunnel to its true lowest-energy state, dissolving the matter of the universe, resetting it to a hot and unstructured state. Or, maybe we're making dire predictions with too little information. What if there is new physics between the settled lands of the standard model and the too-distant island of the Planck scale? Maybe supersymmetry or superstring theory can gallop in here to settle this issue, helping us to understand whether or not the universe is settled on its foundation. Indeed, we can see how complex the Higgs sector of physics becomes when one adds supersymmetry to the standard model. Can the Higgs light the way to some new, intermediate land that soothes this question?

Dark matter is a central mystery of the cosmos today. What are its constituents? Are they heavy, weakly interacting particles? If so, are those interactions truly "weak" in the standard model-sense, governed by Z and H bosons? A great deal of that idea has been ruled out by the steady upward march of sensitivity in the design of direct detection dark matter experiments, but there is room left for this idea to triumph. Ah, but perhaps dark matter is as complex as the standard model, with a myriad of its own matter and force particles. Could the Higgs serve as a "portal" between the standard model and the dark sector?

And what of the Higgs and superstring theory? The discovery of the Higgs boson with a mass of approximately 125 (in appropriate units of measure) is tantalizing from the point of view, not of Superstring/M-Theory per se, but from the point of view of the existence of supersymmetry as an accurate description of our universe. Supersymmetry is a kind of balance in our cosmos between the types of particles that are bosons/fermions on one hand versus those that are carriers subject to the fundamental forces on the other.

Mathematical consistency allows for the mass of the Higgs boson to be much larger, say between 500 and 600 on our appropriate scale. Therefore, the one discovered at 125 GeV/c2 is considered "light." But we've seen earlier how quantum mechanics, if not hand-tuned carefully by the theoretical physicist, could keep driving the expected Higgs mass higher and higher. Yet such ferocious corrections are not seen in the laboratory. Perhaps it is supersymmetry that answers the question of "why not?"

The Higgs boson can be regarded as being analogous to a tightrope walker dealing with blowing winds. If the wind blows too hard from left to right, the performer risks being blown off on the right side of the tightrope. If the wind blows too hard from right to left, the performer risks being blown off on the left side of the tightrope. However, if a wind coming from both directions blows equally hard, then the walker stands a good chance to successfully complete the rope walk.

The mathematical condition of supersymmetry is equivalent to the winds from both directions blowing equally hard. So long as it is in force the Higgs boson could maintain its light mass.

So, is the light mass of the Higgs an effect of Superstring/M-Theory or not?

The answer is confusing. It could be an indication inasmuch as almost all consistent string theories involve supersymmetry. However, it is possible to mathematically construct equations that possess the property of supersymmetry in extensions of the standard model, yet are totally independent of any string theory. So the presence of supersymmetry, while encouraging for string theory, does not provide iron-clad evidence for string theory.

Finally, whether or not the Higgs boson is a "portal" to dark matter is another tantalizing possibility on the horizon. In order to have a mathematically consistent set of equations that include the standard model and supersymmetry, five Higgs bosons are required as well as an equal number of superpartners. So it is conceivable that within this zone there exists a particle type that could explain dark matter.

In truth, the question of "What the heck's the Higgs?" drives a complex and diverse program of physics set to operate for decades to come. The LHC experiments will continue into the 2030s, and there are already plans underway to construct a new facility, perhaps in Japan or in China (or both), to collide electrons and positrons to study the Higgs employing alternative means than presently. These experiments would allow the properties of the Higgs boson to be known to better than 1% precision, the level at which we presently understand many of the other parameters of the standard model.

There is the hope that, with lessons learned from the construction and operation of the LHC, a new proton collider will be built in this century that achieves a new level of proton collision energy at the level of 100 TeV, as compared to the present 14 TeV design of the LHC. We know from past experience that each new increase in energy is accompanied by new discoveries. However, what we learn at the LHC about the Higgs and its interactions may not be sufficient to light the way forward, and we may have to work on a new *discovery machine* that can achieve that step.

The discovery of the Higgs boson was a first step in a much grander journey that will be executed by thousands upon thousands of physicists, theoretical and experimental alike, along with engineers, technicians, and data scientists working on collider and non-collider physics experiments. We now have a Higgs boson, yes, but the final answer to a most basic question, one that has driven the subtitle of this book, lies ahead of us. Perhaps one of our young readers will be inspired to take up this question as their life's work—to be the one who finally cracks it wide open to expose to full light all those myriad forms that continue to cast their questioning shadows upon the cave's wall.

Epilogue

A Glimpse into the Near Future

The physics community will continue its focus on resolving the many unanswered questions about our universe. While this quest has not yet yielded a complete answer as to how the universe operates, as indeed it may never so do, with each new step into the light this sheds, the community encounters even more fundamental and even deeper questions than were earlier revealed.

Even with our detailed present understanding of ordinary matter, there are so many unsettled subjects. Unanswered questions are opportunities for people to make breakthroughs and discoveries in the future. As we have seen, even the mature ideas of string theory and the braneworld concept have unfinished business, and cannot yet yield an accurate picture of reality. We wish to leave you with a sense of wonder at the power of humanity to understand the universe, but we also wish to leave you with the reality that there are many, fundamental, unsolved problems. Each of these is an opportunity, not a crisis.

This era we live in right now is very similar to the one that occurred at the end of the 1800s. That era, too, had reached a moment of wondrous understanding of the universe, having resolved many successful ideas: Newton's Laws, the Laws of Thermodynamics, and Electromagnetism (using Maxwell's Equations). Still, there were puzzle pieces that didn't fit into the then-accepted explanations of nature. Why did atomic spectra exhibit a structure of bright bands and dark bands? Why do bodies that absorb all frequencies of electromagnetic radiation emit a spectrum of radiation so different from that predicted by thermodynamics? Why are some atoms unstable, emitting energy spontaneously? And, of course, there was the mystery of the speed of light: why did it not change when the motion of the source (or the observer) changed? And just what was light? Was it a wave or a particle?

Those mysteries unsettled many physicists. It turns out that these puzzle pieces that didn't quite fit into accepted mathematical explanations were the gateways to new discoveries. These days, we (physicists and non-physicists alike) look romantically back on the early 1900s as a renaissance in physical thought, but a renaissance was possible only because there were unsettled issues.

Let us deal with the question of fundamental mass for the matter found in the universe. While many exploratory ideas about matter bubbled up across the decades, there is but one (so far) that wins the day—the existence of the Higgs boson makes two features of nature possible. It explains why the weak force is so short in range while the electromagnetic force is infinite in range, as well as providing an origin for fundamental mass in matter. The Large Hadron Collider and the thousands of physicists who perform experimental physics using this frontier machine provided the crucial evidence that demonstrated the existence of the Higgs boson. Having concluded nearly fifty years developing this idea, we now begin a decades-long program to further define this new particle.

There is clearly much more needing understanding about the cosmos. Let us again consider ideas like superstring theory and braneworlds. While they are presently far removed from the kind of now-proven reasoning that led to the prediction of the Higgs boson, these ideas have begun to yield experimentally testable consequences that can be probed in current and future experiments. They are ideas within the grasp of near-term research efforts that will be explored during the next decade. This work will seek to reveal a fuller picture of the cosmos—a hidden cosmos that shapes our observable one. That picture will be a grand one—if it is true!

As the writing of this book concludes, the program to understand the Higgs boson is in its early stages. We have pictured that the Higgs boson is a kind of road sign that points on to potential pathways to take us into farther frontiers of human understanding. The Higgs boson provides a foundation upon which physicists will build to increase the understanding of realities that continue for the moment to remain in the shadows. There could be other versions of the Higgs boson, subatomic cousins that await discovery at the LHC that will paint a fascinating "family portrait" hinting additional roles in the cosmos, its possible connection to quantum gravity and the graviton, and even to mathematical symmetries that lie outside the standard model. The discovery of a Higgs boson that is curiously low in mass encourages physicists to think that these kinds of discoveries may be just around the corner.

For decades, one of the most widely explored ways of achieving the prospect for a unified theory of all of nature has been string theory. While mathematically consistent (as all explanations of nature must be to be acceptable), it needs provable evidence showing its accuracy in describing nature—at the smallest scales seen in collider data, at the largest scales seen in the light left over from the big bang, and by astrophysical and cosmological observation. It is of note that *only* string theory, among the unified theories, currently attempts to include the force of gravity in its *quantum* aspects. We must recall Sheldon Glashow's criticism that there is a danger that such models are permanently safe from falsification. We reinforce this criticism by noting that there is presently the inability even to count all of the possible ways to compactify the small extra dimensions in M-theory.

Braneworld models are less complex than are string theory models, thereby supporting an effective means for study through near-term experimentation. While a few braneworld models have been discussed in this book, other iterations aimed at a better description of nature are possible. Many models can be described that synthesize reality, but they will continue to be speculative so long as their predictions remain unverifiable by experiment. Warped extra dimensions are a key player required in this landscape of higher dimensional thinking. The LHC will provide the ability to probe for such features of nature during the next decade.

Particle collider experiments at the LHC will search, within controlled conditions and at higher energies, as technology permits it to do so, aspects of the subatomic realm that are predicted by models built upon the ideas of extra dimensions, supersymmetry, or superstrings. However, colliders are not the only way to do this.

The kinds of research performed with colliders may seem very different from that performed with telescopes or other instruments designed to view the largest structures in the cosmos. However, if physics has taught us anything it is this: there is a harmony among all the scales at which one can view the universe. The structure of the nucleus is the result of the details of the strong force, quarks, and gluons, viewed from a scale far larger than any of those ingredients. The atom is a representation of the details of the nucleus, electrons, and the electromagnetic force working together and viewed from a scale larger than each of those parts. Molecules, and even the stuff of life, are but the details of how atoms behave when viewed from distances far larger than the size of atoms. Matter that is on the scale of human beings (things sized similar to ourselves) has its properties determined by all of the aforementioned microscopic details added together into vast structures we call "the everyday world." The solar system is but the structuring of matter by gravity, as viewed on scales much larger than the human scale, going on to view from ever-larger scales, until we can imagine the entire cosmos—the details of the whole are dictated by the details of the tiniest parts. Viewed in this way, there is no difference between the research conducted at a collider and the research conducted at a telescope. To understand the universe we need to combine all of these pursuits to make progress.

Astrophysical observation of objects such as black holes, neutron stars, supernovas, and gamma-ray bursts provide an excellent means to search for evidence of new phenomena and synergies in the natural world. A collection of large telescopes, telescope arrays, and satellites will observe the sky for decades to come, capturing huge amounts of data at finer and finer scales, searching for hints of anything beyond what we already know about the cosmos. Experiments that hunt for dark matter's constituents will probe the universe in other ways, searching for new particles beyond those encoded in the standard model. The dark matter that shaped the evolution of galaxies, clusters, and superclusters should be all around us; we need only cleverness and patience to figure out from what it is made. If it is made from something other than matter, something of which we have yet to conceive, then we need mathematical cleverness to ascertain its possible natures and devise new tools to study it.

Although they have very tiny masses, neutrinos have performed a role in shaping the cosmos as it is today. If they had been even a little heavier than they are now, the sum total of their effect on the early cosmos will have left a measurable imprint on the cosmic microwave background and, indeed, on the distributions of galaxies in the sky. It is crucial that we use ever more defining experiments to map the properties of neutrinos to further enable a complete understanding of the universe.

Some neutrino experiments will seek to determine the exact mass of each kind of neutrino; some will attempt to determine the nature of its wave behavior; yet others will hunt for signs that matter and anti-matter neutrinos behave differently from each other.

Gravitational wave observatories, having embarked on a new land-based form of astronomy, will read messages in space-time—some of these messages that come to us are viewed as the subtle squashing and stretching of our planet as space-time wobbles emanating from the event horizons of colliding black holes. Gravitational waves will allow us to make "sonograms" of the universe.

Data from any of these methods, along with observational methods not yet developed, will provide unexpected support for one or more of the various mathematical constructions presently extant—braneworlds, supersymmetry, superstring/M-theory—and others yet to be conceived.

Some braneworlds possess properties that may explain the unification of forces. The features of these models (large extra dimensions, warped extra dimensions, or the presence of heavy graviton Kaluza-Klein particles, that could manifest in our 4-dimensional space-time) are intriguing signatures to be searched for with existing or anticipated near-future experiments. Braneworlds have apparent deficiencies══there is no clear limit as to how long these models can continue to evade detection before they are deemed truly falsified.

A Glimpse into the Farther Future

Future research, extending across many decades, will focus in a variety of areas. The list is long: increased understanding of the Higgs boson; continued searching for unpredicted structures and patterns in ultramicroscopic realms; exploring the frequency spectrums of radio—infrared, visible, ultraviolet, x-ray, gamma-ray; knowing more about gravitational wave astronomy; dark matter; dark energy; supersymmetry (and other possible symmetries); the possibility of extra dimensions and its associated mathematics; additional Superstring/M-theory development; and, perhaps, some areas not yet identified by mathematics.

Following are some snapshots of experiments that will soon come on line or were actively being conducted at the time of this book's publication (and are expected to continue to run for years onward). Collider physics will continue to be dominated by the LHC well into the 2030s. While a future collider project might ramp up during that period, construction of such facilities requires decades of planning, building, and shake-down before the first well-understood data becomes available. For example, the LHC was conceived of in the early 1980s and provided its first collisions in 2010, a span of about thirty years.

The present LHC program will focus on the study of the Higgs boson and its connection to new models of physics; on supersymmetry and other scenarios; and the study of nuclear collisions, which can teach us about a "quark-gluon fog" that should have existed during the period immediately after the big bang occurred. These and many other areas of study will be accessible to specialized and multi-purpose particle detector experiments at the LHC. The low mass of the Higgs boson has provided a boost for the expectations of the supersymmetry community by pointing indirectly to the possibility for extending the standard model using SUSY. The community continues to look for direct evidence of the existence of this long-sought and intriguing but elusive symmetry of nature.

Astronomy is engaged in a diverse portfolio of experiments. The James Webb Space Telescope, successor to the Hubble Space Telescope, is expected to launch in Spring, 2019. It will bring us new and incredible images from deep space that will be well beyond the technical abilities that were the Hubble's. The Large Synoptic Survey Telescope (LSST), a land-based telescope in northern Chile, is scheduled to be built and begin operations in early 2022. Capable of scanning large sections of the sky very quickly (attributable to its extremely high resolution of 3.2 gigapixels), LSST will build a huge catalog of astronomical objects meant to better understand the evolution of the universe and the physical nature of astronomical phenomena.

A series of telescopes, both ground-based and balloon-borne, will probe the light from the big bang and the cosmic microwave background looking for evidence of gravitational waves that would have been imprinted on that light dating from the birth of the cosmos. Gravitational wave interferometer experiments, such as LIGO and Virgo, are the vanguard of a new generation of space-time telescopes. So far, they have heard the chirps in space-time that emanate from colliding black holes. As more such amazing phenomena are observed, one can only speculate on the new information that will be learned about the universe during the coming decades.

In the area of high-energy particle astronomy, the AMS-02 experiment located on the international space station is a major instrument for studying particles arriving from outer space. Gamma ray satellites such as the Fermi Gamma-Ray Space Telescope will continue to look at the most cataclysmic phenomena in the cosmos, teaching us about the deaths of stars and even larger objects, including the feeding behavior of supermassive black holes. Neutrino telescopes like IceCube at the south pole or ANTARES in the Mediterranean Sea are capable of detecting the highest-energy neutrinos in the universe, and are thus expected to teach us about the kinds of extreme phenomena capable of producing these neutrinos.

The dark matter search community will be very busy for at least one or two decades. The next generation of dark matter search experiments, such as LUX-ZEPLIN (LZ), SuperCDMS SNOLAB, XENON1T, and ADMX Gen2, will push the boundaries of sensitivity while searching for ultra-low-mass dark matter (millionths of the proton mass), low-mass dark matter (less than ten times the proton mass), and heavy dark matter (greater than ten times the proton mass). Eventually, these experiments will become so sensitive to particle interactions that even the very-low-energy neutrinos emitted by our sun may be easily spotted by these instruments, but that is probably still a decade away. Orbital and ground-based astronomy experiments will also be on the hunt for dark matter in the cosmos, looking for interactions where dark matter might clump in our universe—at the centers of galaxies and, perhaps, even in the hearts of stars. The LHC will also participate, looking for the production of dark matter particles in the collider.

Neutrino experiments are expected to be of great interest over the coming decades. In addition to presently operating experiments like T2K in Japan and NOvA in the United States, there is the expectation of a next-generation program called DUNE/LBNF (Deep Underground Neutrino Experiment/Long-Baseline Neutrino Facility). These international programs are studying neutrinos very carefully, mapping out their properties as they observe mixing among their various kinds. Over the coming decades, the neutrino will be coaxed to yield its secrets. It has already provided many surprises. What, for example, might it tell us about the origin of mass?

Let us recall a subject we have looked at in detail from multiple perspectives: the implications for experiments as to whether extra spatial dimensions actually exist. What if these dimensions are large? The most popular reason for invoking extra dimensions is to explain the relative weakness of gravity as compared to the other forces of nature. If gravity does travel in these extra dimensions, thereby weakening its influence in the space and time dimensions by spending little time in our own brane, this can be detected by studying how gravity changes strength on small scales; or, by searching for evidence that particles of gravity—gravitons—travel in the extra dimensions and appear to us, in our four dimensions, as though they are a zoo of new heavy particles (Kaluza-Klein particles). Neither of these effects have been observed, but they continue to be hunted. This has constrained the original breadth of these ideas, limiting possible detectable effects. Kaluza-Klein particles might just be heavier than our present ability to produce them at the LHC. Or, maybe large extra dimensions are not as large as we hoped they might be, or that they are more numerous than we would prefer. If there are more than just one or two extra dimensions, there are more places for Kaluza-Klein particles to have extra momentum, raising the smallest masses they would appear to possess in our 4-dimensional space-time and putting them further from the reach of the LHC. Or, perhaps they don't exist at all! Experiment has ruled out the simpler possibilities, but has not ruled out the idea entirely.

What would it mean if experiments like those at the LHC or in the dark matter search community were to fail to observe anything beyond what is presently and comfortably explained in the standard model? The absence of SUSY in the realm of elementary particles would likely make most superstring concepts less attractive for study (although we note that the failure to detect SUSY since its prediction in the 1970s has not thus far wholly dissuaded the superstring theory community from its pursuit). Alternately, perhaps SUSY particles are trapped on a brane we cannot yet (or ever) access with experiments, making them untestable and thus unsuited to the physical description of nature. Finding new SUSY constructs would require a fresh look at how 4-dimensional and extra-dimensional versions of string theory would avoid their own demise. Because SUSY is a framework that can accommodate many models, its data cannot be used to provide an iron-clad rigorous argument against SUSY. There is an omnipresent danger that the only tenable models of SUSY or extra dimensions will be those that allow for our universe to be as it exists in nature while all the models' novelties (the traits that distinguish them) are not directly provable. In such a case, they would become more a kind of mathematical philosophy than a physical theory.

We remind the reader again that the true test of any good description of the natural world is through experiment and observation; failure to detect direct evidence for an idea means that that concept may be wrong, or, at the least, not relevant. Recall that the expectation for and the implications for the existence of a Higgs boson were conceived of in the early 1960s. The standard model incorporated these ideas and *indirect* evidence for the Higgs boson was collected from the early 1980s until the early 2000s, yet the Nobel Prize (we use the Nobel here as a proxy for a community having truly accepted an idea as "correct") was not awarded for this mechanism until it was definitively detected and confirmed during 2012–2013, the prize having then been awarded in 2013. Direct evidence is the cornerstone of any successful theory of nature.

We also remind the reader that models—specific mathematical constructs designed to allow for near-term experimental testing—are more easily refuted than are the frameworks upon which they are built. Braneworlds are built upon the notion of extra dimensions; failure to detect evidence of a specific braneworld model is not the same as falsifying the existence of extra dimensions. While it might be possible to rule out the RS-1 or RS-2 braneworld models by the end of the LHC program, that is not evidence against extra dimensions. The theoretical physics community will have to work very hard, as they have in building other frameworks (such as the standard model), to find the clear boundaries of these mathematical ideas in which absolute falsifiability is then achieved. This is probably the most difficult task the community of mathematical explorers will have to undertake in the coming decades.

Competition among ideas is crucial to this process. Let us consider superstring theory as one arena in which competition may prove extremely useful at separating valid from useless ideas. If there are only five dimensions, not ten or eleven, the mathematics of strings cannot (in its present form) describe our universe. If there are ten or eleven dimensions, we need to know where they exist—if they are curled up and hidden, or perhaps they disappeared after the big bang. Maybe, as we warned in earlier chapters, the problem of dimensionality is a red herring, a misleading folly, since the inception of bosonic string theory in the 1970s. Multiple dimensions were, in many ways, the primary problem of the theory and the concept on which tremendous intellectual effort was spent trying to explain the non-observation of so many necessary extra dimensions.

Perhaps this was a false flag from nature, a curiosity in the mathematics that distracted us from a better course, causing us to seek to make superstring theory work in the four space-time dimensions we know for certain do exist. As we have illustrated, the casting of such dissident concepts (this one has been championed, as we have noted, by one of the authors of this book, SJG) into the intellectual ecosystem are crucial, if only to spur on a community of thinkers to get out of its rut. Who can say which idea will be the right idea? Only experiment can sort that out, but if not all of the potential ideas have been trotted out, then one won't know to test for the one that may be the correct one.

If we were to observe generalities for a moment, we would suggest that the discovery of new particles in nature (wherever such a discovery might arise, whether in dark matter detectors, the LHC, astrophysical observations, or any other) appears to be crucial to further progress in answering the big questions that face the physics community. If we want to explain why the standard model over-predicts the energy of empty space (vacuum energy, a possible source for dark energy), there may need to be more particle interactions to cancel out those in the standard model. This is also true if we want to understand the relative lightness of the Higgs boson mass or if we want to understand dark matter. Kaluza-Klein excitations of the graviton are a key prediction of warped extra dimensions—these are another class of new particle looking to be found, if they exist. It seems that in most of the places we look, where there exist mature theoretical notions for a more generic mathematical description of nature, new particles are required as a path to completion of those ideas.

Another intriguing possibility that we will leave for the reader to consider is the possibility for the disappearance of some particles at high energy levels. If high energies are required to observe extra dimensions, we might first discover that the disappeared particles are traveling in extra dimensions by noting their absence during collider experiments. We looked briefly at this concept in the later chapter on the Higgs boson, while discussing the idea of invisible Higgs boson decay. Search strategies could reveal that particles at the highest energies are regularly missing from the detectors, even though we expect them to be found there. While hunting for extra dimensions, the disappearance of something old might be just as important as the appearance of something new.

Looking back deeper in time, by studying the light from the big bang (or maybe one day, when the technology permits, neutrinos that are left over from the big bang), is intended to give us more information about the first instants of time when the universe came into being. Mathematically based braneworld models offer the possibility to explain how the big bang might have occurred in the first place—by the collision of two nearby branes. Can the fingerprints of such occurrences be detected as we become able to peer closer and closer to the first instant of time?

A model of this kind of brane-induced big bang was proposed by Justin Khoury, Burt Ovrut, Paul Steinhardt, and Neil Turok in 2001. Their "ekpyrotic model" moved braneworlds in a new direction. They found that, after such a collision, there can be derived a set of mathematical equations that describes a universe much like the one we live in! As with any new idea in physics, serious technical challenges have been raised about this model, but still, one can see how branes have taken physicists on a path to consider new perspectives about what it means to be "in a universe." If branes can collide once, why not more than once? And what if *multiple* branes are capable of colliding? What happens when they *do* collide en masse? Many new questions emerge to join the shadows! It would not be improbable to continue carrying further questioning into even deeper, darker corners of the shadows.

Until positive proof arising from direct observation and experiment occurs, superstring/M-Theory, braneworld scenarios, and whatever other ideas will emerge from the fertile imaginations of theorists, these ideas must continue each to be borne into a shadow of reality. Each is an enigma to be resolved in the expectation that we are bringing them a light-step forward, rather than casting them into new darkness in the cosmos. Observation is the true test of hypothesis. When observation yields direct evidence, we will have met the challenge of bringing reality out of the shadows.

About the Authors

S. JAMES GATES, Jr's (Jim Gates) interest in science began at age four when his mother, Charlie, brought her children to a science fiction movie when the family was living at Ft. Pepperell near St. John's, Newfoundland. Four years later at Ft. Bliss, near El Paso, Texas, Sylvester James Gates, Sr., his father—a member of the U.S. Army and a veteran of WWII—gave him books about the coming of the space age that solidified an early interest in science (and kindled his wish to become an astronaut). Science fiction, comic book superheroes, a fantastic high school physics teacher, Mr. Freeman Coney, and the Orlando Public Library served as the launch pad for a life in physics.

Gates became the Ford Foundation Professor, Physics and Affiliate Professor of Mathematics at Brown University in Providence, Rhode Island after retiring in 2017 as a University System Regents Professor; Center for String and Particle Theory Director; Distinguished University Professor; John S. Toll Professor of Physics; and Affiliate Professor of Mathematics at the University of Maryland—College Park.

He received the 2011 National Medal of Science, the 2006 Public Understanding of Science & Technology Award from the American Association for the Advancement of Science, the 2003 Klopsteg Award for excellent physics teaching from the American Association of Physics Teachers, and the 1994 Bouchet Award of the American Physical Society. He is a member of the National Academy of Science, the American Association for the Advancement of Science, the American Academy of Arts and Sciences, the American Physical Society, and the American Philosophical Society.

Gates has contributed to the mathematical foundation of supersymmetry since authoring M.I.T.'s first Ph.D. written on the subject in 1977. Among his discoveries has been four dimensional string theory using the mathematics of the standard model and connections to graph theory, information theory, and indications of the possibility that following the big bang there might have been an "inchoate epoch" during which processes similar to evolution acted on the mathematical laws that describe our universe. His research continues to expand the understanding of supersymmetry in unique and innovative ways.

In 2017, he completed forty-five consecutive years as a college instructor in physics and/or mathematics. He has appeared in many TV science documentaries, on-line videos, and in 2006 completed *Superstring Theory: The DNA of Reality,* a video series of twenty-four half-hour non-technical presentations.

FRANK BLITZER received his B.S.E.E from Purdue University with a second major in mathematics. After graduating, he continued his studies toward the Master's Degree in Electrical Engineering. Frank spent fifty years working for several major companies in the aerospace industry on such things as the design of the B-52 bomber and various missiles and space systems. He facilitated operations with inertial guidance, communications, and surveillance systems. He contributed to the design of systems for the Lacrosse Missile, Patriot Missile, the APOLLO Manned-Space Program, and the Strategic Defense Initiative Program. He developed and patented several missile guidance and control systems, and space systems, as well as pattern recognition and surveillance systems, in which fields he is published. He received the Honeywell Top Performer Award in 1992.

STEPHEN JACOB SEKULA's parents, Annetta and Stephen, fed Steve's early science habits with dangerous chemistry sets, providing his writing interest with endless pads of paper, typewriters, and, eventually, word processing software, as well as intellectual criticism of that writing. His sister, Kate, was essential in dragging him back to reality when he spent too much time in the same shadows this book explores.

SJS is Associate Professor of Experimental Particle Physics at Southern Methodist University in Dallas, Texas. He earned his Ph.D. from the University of Wisconsin–Madison and his B.S. from Yale University.

He has been involved in particle collider experiments since his undergraduate days; first at Fermilab, then at SLAC National Accelerator Laboratory, and presently at CERN. He led a team within the BaBar collaboration in 2008 that discovered a state of matter, the lowest energy configuration of bottom quark and its antimatter counterpart, that was first predicted to exist in 1977. He participated in the discovery and measurement of the Higgs Boson in 2012 and 2013, culminating in the announcement of its discovery on the Fourth of July in 2012. He continues still to be facinated by the potential of this particle to explain even more about the presently unknown origins of our universe.

He is a recipient of the 2017 SMU Altshuler Distinguished Teaching Professor Award and he received the Texas Section American Physical Society's Robert S. Hyer Award for excellence in the supervision of undergraduate research.