UNDERSTANDING THE UNIVERSE

from Quarks to the Cosmos

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UNDERSTANDING THE UNIVERSE

from Quarks to the Cosmos

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To

*Sharon for giving me life,
Diane for making it worthwhile*

&

*Tommy, Veronica and David for making it interesting
and to*

*Marj Corcoran, Robin Tulloch, Charles Gaides and all the others
for directions along the path.*

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Foreword

One hot summer day in July of 392 BC, it might have been a Tuesday, the Greek philosopher Democritus of Abdera asserted that everything we see is made of common, fundamental, invisible constituents; things that are so small we don't see them in our everyday experience. Like most great ideas, it wasn't exactly original. Democritus's teacher, Leucippus of Miletus, probably had the same atomistic view of nature. The concept of atomism remained just a *theory* for over two millennia. It wasn't until the 20th century that this exotic idea of "atoms" proved to be correct. The atomistic idea, that there are discernable fundamental building blocks, and understandable rules under which they combine and form everything we see in the universe, is one of the most profound and fertile ideas in science.

The search for the fundamental building blocks of nature did not end with the 20th century discovery of atoms. Atoms are divisible; inside atoms are nuclei and electrons, inside nuclei are neutrons and protons, and inside them are particles known as quarks and gluons. Perhaps quarks are not the ultimate expression of the idea of atomism, and the search for the truly fundamental will continue for another century or so. But they may be! What we do know about

quarks and other seemingly fundamental particles provides a remarkably complete picture of how the world works. In fact, not only of how the world works, but of how the entire cosmos works!

The study of nature is traditionally divided into different disciplines: astronomy, biology, chemistry, geology, physics, zoology, etc. But nature itself is a seamless fabric. The great American naturalist John Muir expressed this idea when he said, "When we try to pick out anything by itself, we find it hitched to everything else in the universe." When Don Lincoln and his colleagues at Fermilab in Batavia, Illinois explore the inner space of quarks they are also exploring the outer space of the cosmos. Quarks are hitched to the cosmos. Understanding nature's fundamental particles is part of the grand quest of understanding the universe. Don Lincoln never lets us forget that on this journey from quarks to the cosmos! The spirit of Leucippus of Miletus and Democritus of Abdera is still alive in Don of Batavia.

Don is a physicist at Fermi National Accelerator Laboratory (Fermilab), the home of the Tevatron, the world's most powerful accelerator. Currently Don is a member of one of the two very large colliding beams experiments at Fermilab. Such experiments are dedicated to the study of the nature of fundamental particles when protons and antiprotons collide after being accelerated near the velocity of light. He works at the very frontier of the subject about which he writes.

Don writes with the same passion he has for physics. After years of explaining physics to lay audiences, he knows how to convey the important concepts of modern particle physics to the general public.

There are many books on fundamental particle physics written for the general public. Most do a marvelous job of conveying what we know. Don Lincoln does more than tell us *what* we know; he tells us *how* we know it, and even more importantly, *why* we want to know it!

Understanding the Universe is also a saga of the people involved in the development of the science of particle physics. Don tells the story about how an important experiment was conceived over a lunch

of egg rolls at New York's Shanghai Café on January 4th, 1957. He also describes life inside the 500-person collaboration of physicists of his present experiment. Great discoveries are not made by complex detectors, machinery, and computers, but by even more complex people. If you ever wondered what compels scientists to work for years on the world's most complicated experiments, read on!

Rocky Kolb
Chicago, Illinois

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Preface (And so ad infinitum)

The most incomprehensible thing about the universe is that it's comprehensible at all ...

— Albert Einstein

The study of science is one of the most interesting endeavors ever undertaken by mankind and, in my opinion, physics is the most interesting science. The other sciences each have their fascinating questions, but none are so deeply fundamental. Even the question of the origins of life, one of the great unanswered mysteries, is likely to be answered by research in the field of organic chemistry, using knowledge which is already largely understood. And chemistry, an immense and profitable field of study, is ultimately concerned with endless and complicated combinations of atoms. The details of how atoms combine are rather tricky, but in principle they can be calculated from the well-known ideas of quantum mechanics. While chemists rightfully claim the study of the interactions of atoms as their domain, it was physicists who clarified the nature of atoms themselves. Although the boundaries between different fields of scientific endeavor were

somewhat more blurred in earlier eras, physicists first discovered that atoms were not truly elemental, but rather contained smaller particles within them. Also, physicists first showed that the atom could in some ways be treated as a solar system, with tiny electrons orbiting a dense and heavy nucleus. The realization that this simple model could not possibly be the entire story led inexorably to the deeply mysterious realm of quantum mechanics. While the nucleus of the atom was first considered to be fundamental, physicists were surprised to find that the nucleus contained protons and neutrons and, in turn, that protons and neutrons themselves contained even smaller particles called quarks. Thus the question of exactly what constitutes the smallest constituent of matter, a journey that began over 2500 years ago, is still an active field of scientific effort. While it is true that our understanding is far more sophisticated than it was, there are still indications that the story is not complete.

Even within the field of physics, there are different types of efforts. Research into solid state physics and acoustics has solved the simple questions and is now attacking more difficult and complex problems. However, there remain physicists who are interested in the deepest and most fundamental questions possible. There are many questions left, for example: What is the ultimate nature of reality? Are there smallest particles or, as one looks at smaller and smaller size scales, does space itself become quantized and the smallest constituents of matter can be more properly viewed as vibrations of space (the so-called superstring hypothesis)? What forces are needed to understand the world? Are there many forces or few? While particle physicists can hope to study these questions, the approach that they follow requires an ever-increasing concentration of energy into an ever-decreasing volume. This incredible concentration of energy has not been generally present in the universe since the first fractions of a second after the Big Bang. Thus, the study of particle physics provides guidance to another deeply fundamental question, the creation and ultimate fate of the universe itself.

The current state of knowledge cannot yet answer these questions, however progress has been made in these directions. We now

know of several particles that have thus far successfully resisted all attempts to find structure within them. The particles called quarks make up the protons and neutrons that, in turn, make up the atom's nucleus. Leptons are not found in the nucleus of the atom, but the most common lepton, the electron, orbits the nucleus at a (relatively) great distance. We know of four forces: gravity, which keeps the heavens in order and is currently (although hopefully not forever) outside the realm of particle physics experimentation; the electromagnetic force, which governs the behavior of electrons around atomic nuclei and forms the basis of all chemistry; the weak force, which keeps the Sun burning and is partly responsible for the Earth's volcanism and plate tectonics; and the strong force, which keeps quarks inside protons and neutrons and even holds the protons and neutrons together to form atomic nuclei. Without any of these forces, the universe would simply not exist in anything like its current form. While we now know of four forces, in the past there were thought to be more. In the late 1600s, Isaac Newton devised the theory of universal gravitation, which explained that the force governing the motion of the heavens and our weight here on Earth were really the same things, something not at all obvious. In the 1860s, James Clerk Maxwell showed that electricity and magnetism, initially thought to be different, were intimately related. In the 1960s, the electromagnetic and weak forces were actually shown to be different facets of a single electro-weak force. This history of unifying seemingly different forces has proven to be very fruitful and naturally we wonder if it is possible that the remaining four (really three) forces could be shown to be different faces of a more fundamental force.

All of creation, i.e. all of the things that you can see when you look about you, from the extremely tiny to the edge of the universe, can be explained as endless combinations of two kinds of quarks, an electron and a neutrino (a particle which we haven't yet discussed). These four particles we call a generation. Modern experiments have shown that there exist at least two additional generations (and probably only two), each containing four similar particles, but with each

subsequent generation having a greater mass and with the heavier generation decaying rapidly into the familiar particles of the first generation. Of course, this raises yet even more questions. Why are there generations? More specifically, why are there three generations? Why are the unstable generations heavier, given that otherwise the generations seem nearly identical?

Each of the four forces can be explained as an exchange of a particular kind of particle, one kind for each force. These particles will eventually be discussed in detail, but their names are the photon, the gluon, the W and Z particles and (maybe) the graviton. Each of these particles are bosons, which have a particular type of quantum mechanical behavior. In contrast, the quarks and leptons are fermions, with completely different behavior. Why the force-carrying particles should be bosons, while the matter particles are fermions, is not understood. A theory, called supersymmetry, tries to make the situation more symmetric and postulates additional fermion particles that are related to the bosonic force carriers and other bosonic particles that are related to the mass-carrying fermions. Currently there exists no unambiguous experimental evidence for this idea, but the idea is theoretically so interesting that the search for supersymmetry is a field of intense study.

While many questions remain, the fact is that modern physics can explain (with the assistance of all of the offshoot sciences) most of creation, from the universe to galaxies, stars, planets, people, amoebae, molecules, atoms and finally quarks and leptons. From a size of 10^{-18} meters, through 44 orders of magnitude to the 10^{26} meter size of the visible universe, from objects that are motionless, to ones that are moving 300,000,000 meters per second (186,000 miles per second), from temperatures ranging from absolute zero to $3 \times 10^{15}^\circ\text{C}$, matter under all of these conditions is pretty well understood. And this, as my Dad would say, impresses the hell out of me.

The fact that particle physics is intimately linked with cosmology is also a deeply fascinating concept and field of study. Recent studies have shown that there may exist in the universe dark matter ... matter which adds to the gravitational behavior of the universe, but is intrinsically

invisible. The idea of dark energy is a similar answer to the same question. One way in which particle physics can contribute to this debate is to look for particles which are highly massive, but also stable (i.e. don't decay) and which do not interact very much with ordinary matter (physics-ese for invisible). While it seems a bit of a reach to say that particle physics is related to cosmology, you must recall that *nuclear* physics, which is particle physics' lower-energy cousin, has made critical contributions to the physics of star formation, supernovae, black holes and neutron stars. The fascinating cosmological questions of extra dimensions, black holes, the warping of space and the unfathomably hot conditions of the Big Bang itself are all questions to which particle physics can make important contributions.

The interlinking of the fields of particle physics and cosmology to the interesting questions they address is given in the figure below. The answer to the questions of unification (the deepest nature of reality), hidden dimensions (the structure of space itself) and cosmology (the beginning and end of the universe), will require input from many

Figure The intricate interconnections between the physics of the very small and the very large. (Figure courtesy of Fermilab.)

fields. The particle physics discussed in this book will only provide a part of the answer; but a crucial part and one richly deserving study.

Naturally, not everyone can be a scientist and devote their lives to understanding all of the physics needed to explain this vast range of knowledge. That would be too large a quest even for professional scientists. However, I have been lucky. For over twenty years, I have been able to study physics in a serious manner and I was a casual student for over ten years before that. While I cannot pretend to know everything, I have finally gained enough knowledge to be able to help push back the frontiers of knowledge just a little bit. As a researcher at Fermi National Accelerator Laboratory (Fermilab), currently the highest energy particle physics laboratory in the world, I have the privilege of working with truly gifted scientists, each of whom is driven by the same goal: to better understand the world at the deepest and most fundamental level. It's all great fun.

About once a month, I am asked to speak with a group of science enthusiasts about the sorts of physics being done by modern particle physics researchers. Each and every time, I find some fraction of the audience who is deeply interested in the same questions that researchers are. While their training is not such that they can contribute directly, they want to *know*. So I talk to them and they understand. Physics really isn't so hard. An interested layman can understand the physics research that my colleagues and I do. They just need to have it explained to them clearly and in a language that is respectful of what they know. They're usually very smart people. They're just not experts.

So that's where this book comes in. There are many books on particle physics, written for the layman. Most of the people with whom I speak have read many of them. They want to know more. There are also books, often written by theoretical physicists, which discuss speculative theories. And while speculation is fun (and frequently is how science is advanced), what we *know* is interesting enough to fill a book by itself. As an experimental physicist, I have attempted to write a book so that, at the end, the reader will have a good grasp on what

we know, so that they can read the theoretically speculative books with a more critical eye. I'm not picking on theorists, after all some of my best friends have actually ridden on the same bus as a theorist. (I'm kidding, of course. Most theorists I know are very bright and insightful people.) But I would like to present the material so that not just the ideas and results are explained, but also so that a flavor of the experimental techniques comes through ... the "How do you do it?" question is explained.

This book is designed to stand on its own. You don't have to read other books first. In the end you should understand quite a bit of fundamental particle physics and, unlike many books of this sort, have a pretty good idea of how we measure the things that we do and further have a good "speculation" detector. Speculative physics is fun, so towards the end of the book, I will introduce some of the unproven ideas that we are currently investigating. Gordon Kane (a theorist, but a good guy even so) in his own book *The Particle Garden*, coined the phrase "Research in Progress" (RIP) to distinguish between what is known and what isn't known, but is being investigated. I like this phrase and, in the best scientific tradition, will incorporate this good idea into this book.

Another reason that I am writing this book now is that the Fermilab accelerator is just starting again, after an upgrade that took over five years. The primary goal (although by no means the only one) of two experiments, including one on which I have been working for about ten years, is to search for the Higgs boson. This particle has not been observed (RIP!), but if it exists will have something to say about why the various known particles have the masses that they do. While the Higgs particle may not exist, something similar to it must, or our understanding of particle physics is deeply flawed. So we're looking and, because it's so interesting, I devote a chapter to the topic.

This is not a history book; it's a book on *physics*. Nonetheless, the first chapter briefly discusses the long interest that mankind has had in understanding the nature of nature, from the ancient Greeks until

the beginning of the 20th century. The second chapter begins with the discovery of the electrons, x-rays and radioactivity (really the beginning of modern particle physics) and proceeds through 1960, detailing the many particle discoveries of the modern physics era. It was in the 1960s that physicists really got a handle on what was going on. Chapter 3 discusses the elementary particles (quarks and leptons) which could neatly explain the hundreds of particles discovered in the preceding sixty years. Chapter 4 discusses the forces, without which the universe would be an uninteresting place. Chapter 5 concentrates on the Higgs boson, which is needed to explain why the various particles discussed in Chapter 3 have such disparate masses and the search for (and hopefully discovery of) will consume the efforts of so many of my immediate colleagues. Chapter 6 concentrates on the experimental techniques needed to make discoveries in modern accelerator-based particle physics experiments. This sort of information is often given at best in a skimpy fashion in these types of books, but my experimentalist's nature won't allow that. In Chapter 7, I outline mysteries that are yielding up their secrets to my colleagues as I write. From neutrino oscillations to the question of why there appears to be more matter than antimatter in the universe are two really interesting nuts that are beginning to crack. Chapter 8 is where I finally indulge my more speculative nature. Modern experiments also look for hints of "new physics" i.e. stuff which we might suspect, but have little reason to expect. Supersymmetry, superstrings, extra dimensions and technicolor are just a few of the wild ideas that theorists have that just might be true. We'll cover many of these ideas here. In Chapter 9, I will spend some time discussing modern cosmology. Cosmology and particle physics are cousin fields and they are trying to address some similar questions. The linkages between the fields are deep and interesting and, by this point in the book, the reader will be ready to tackle these tricky issues. The book ends with several appendices that give really interesting information that is not strictly crucial to understanding particle physics, but which the adventurous reader will appreciate.

The title of this preface comes from a bit of verse by Augustus de Morgan (1806–1871) (who in turn was stealing from Jonathan Swift) from his book *A Budget of Paradoxes*. He was commenting on the recurring patterns one sees as one goes from larger to smaller size scales. On a big enough scale, galaxies can be treated as structure-less, but as one looks at them with a finer scale, one sees that they are made of solar systems, which in turn are made of planets and suns. The pattern of nominally structure-less objects eventually revealing a rich substructure has continued for as long as we have looked.

Great fleas have little fleas,
upon their back to bite ‘em,
little fleas have lesser fleas,
and so ad infinitum ...

He goes on to even more clearly underscore his point:

And the great fleas themselves, in turn,
have greater fleas to go on;
While these again have greater still,
And greater still, and so on.

I hope that you have as much fun reading this book as I had writing it. Science is a passion. Indulge it. Always study. Always learn. Always question. To do otherwise is to die a little inside.

Don Lincoln
Fermilab
October 24, 2003

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With their generous help, both the physics and readability of the text have much improved. Any remaining errors or rough edges are

solely the responsibility of Fred Titcomb. Actually, Fred doesn't even know this book is being written and I've seen him rarely these past twenty years, but I've known him since kindergarten and routinely blamed him for things when we were kids. While it's true that any remaining errors are my fault, I don't see any reason to stop that tradition now.

I am grateful to Rocky Kolb for contributing a foreword for this book. Rocky is a theoretical cosmologist with a real gift for science communication. His inclusion in this book is in some sense a metaphor for the book's entire premise...the close interplay between the fields of cosmology and particle physics; experimental and theoretical.

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