The Quantum Frontier

The Large Hadron Collider

Don Lincoln

Foreword by Leon Lederman

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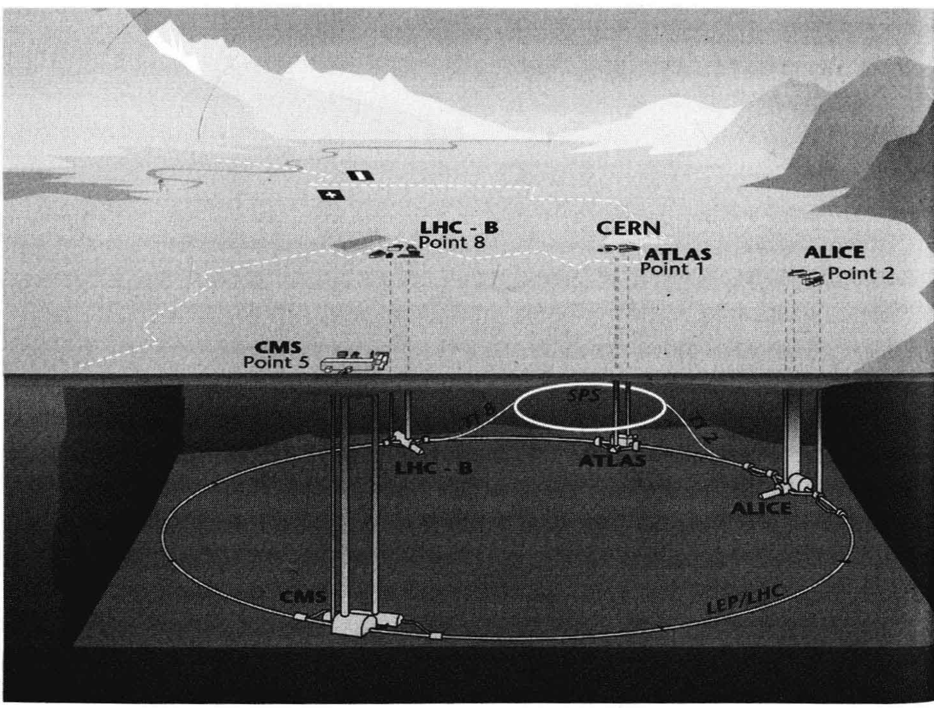

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To those giants on whose shoulders I have stood

Foreword

The Large Hadron Collider, or LHC, is a new scientific tool. The invention of tools, instruments to aid in observation and measurement, has been crucial to the advancement of science. Even though there is a robust debate as to the relative virtues of pure versus applied research, instruments are vital to both branches and serve as a harmonious bridge. In the late nineteenth and early twentieth centuries, progress in both basic research and applied research has been utilized to create ever more powerful tools. Many of these were designed for comfort and entertainment but their use to advance the understanding of nature led the way. It's really cozy: research creates new knowledge, which enables the creation of new instruments, which make possible the discovery of new knowledge.

An example: Galileo constructed many telescopes after hearing about their invention in Holland. In one stunning weekend, he turned a telescope to the sky and discovered four of the moons of Jupiter! This convinced him that indeed the Earth was in motion as surmised by Copernicus. The evolution of telescopes ultimately gave humans a measure of the vastness of our universe with its billions of galaxies, each hosting billions of suns. And in the more sophisticated science, more powerful telescopes were developed.

A further example relevant to our book about the LHC: the structure and properties of electrons are about as basic as one can get in the grand quest for understanding how the world works. But many of these properties make electrons a powerful component in countless instruments. Electrons make x-rays for medical use and for determining the structure of biological molecules. Electron beams make oscilloscopes, televisions, and hundreds of devices found in laboratories, hospitals, and the home.

An impressive technology enabled the control of energetic electron beams in particle accelerators. These were invented in the 1930s and provided precise data on the size, shape, and structure of atoms. To probe the nucleus of atoms, higher energies were required, and the acceleration of protons was added to the toolkit of physicists.

An approximate timetable of progress in accelerators may be useful and is shown below. Note that eV equals one electron volt, so keV is 10^3 electron volts, MeV is 10^6 electron volts, GeV is 10^9 electron volts, and TeV is 10^{12} electron volts. You can see in the table that the higher the energy of the accelerated particle, the smaller the distance probed. However, to probe the very small, the accelerators also grew in size, complexity, and cost. Accelerators are then in essence powerful microscopes, taking over when light is no longer sufficient.

Date	Energy	Distance Probed
1930	~100 keV	10^{-11} meters
1950	~100 MeV	10^{-14} meters
1970	100 GeV	10^{-17} meters
1990	1 TeV	10^{-18} meters
2010	10 TeV	1^{-19} meters
2020	?	?

Over the past 80 years, hundreds of accelerators have been constructed worldwide, predominantly to address the unknowns in the field of particle physics. Other applications of accelerators are these: in medical treatment, as powerful x-ray sources, in industry, and in oil explorations. The complexity and cost of the newer machines have forced large international collaborations. For the first time, construction costs of an accelerator, the LHC, will be shared by Europe, Russia, Japan, China, and the United States.

There is a matching set of requirements for the construction of the detectors (see chapter 4) that must observe the new domain exposed by the accelerators—essentially supermicroscopes. Here, intimate collaborations of over a thousand scientists and students are involved. The official language of these collaborations is, of necessity, "broken English."

It should be noted that, though high energy physics came out of a marriage of nuclear and cosmic ray physics in the late 1940s, we now recognize a new merger of high energy particle physics, which is accelerator based, with astrophysics, which is telescope based. The long-recognized connections of the inner space of particles with the outer space of the cosmos has been reinforced by baffling data on gravitation (dark matter and dark energy) and the continuing mystery of particle symmetry-breaking. However, the "inner space-outer space" connection teaches us that the newly born universe consisted of the elementary particles out of which the stars, galaxies, planets, and people eventually emerged.

So, in the first decade of the twenty-first century, the venerable Tevatron accelerator at Fermilab, born in the scientific dreams of 1985, is operating at full capacity in the hopes of adding to its distinguished list of discoveries before the advent of its CERN (in Geneva, Switzerland—the lab we love to hate) successor, the LHC, scheduled to begin operations in 2008.

At the entrance to the accelerator, the atmosphere is heavy with the promise of discovery. The list of burning open questions today is longer and more profound than that with which we struggled in 1985 (see chapter 5 for a few of today's questions).

Our list of questions will not all be solved by the LHC, and new ones will surely be added. For now, a new generation of accelerators grows in the minds and in the R & D of a new generation of accelerator physicists and their students.

This is a glorious time for them.

But in the meantime, this book by Don Lincoln tells of the excitement experienced by physicists as the LHC commences operations and lets the reader appreciate why the LHC is of such great interest to all physicists. We live in very interesting times.

Leon Lederman

A few quotes as salsa for the repast that awaits you in the journey ahead with Don Lincoln.

One of man's enduring hopes has been to find a few simple general laws that would explain why nature, with all its seeming complexity and variety, is the way it is.

We will still need the LHC to pin down the details of the symmetry-breaking mechanism that gives mass to elementary particles.

Steve Weinberg, Nobel laureate, Physics 1979

The supreme test of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction.

Albert Einstein

When Anton von Leeuwenhoek first saw his "animacules" in a drop of pond water in the seventeenth century, he was in fact extending the ability of humans to see the world in modes not accessible to eyes alone.

The number of dimensions is the number of quantities you need to know to completely pin down a point in space.

Supersymmetry is an extension of known particle physics concepts and has a good chance of being tested in forthcoming experiments. String theory is different.

Lisa Randall, professor of physics, Harvard University

The expanding cloud of billions of galaxies that we call the Big Bang may be just a fragment of a much larger universe in which Big Bangs go all the time, each with different values for the fundamental constants.

Andrei Linde, professor of physics, Stanford University

Every day in a handful of particle accelerators throughout the world, scientists accelerate protons or electrons to tremendous energies and collide them. In these collisions it is possible to create, for a brief instant, the conditions that have not existed in the universe for fourteen billion years.

Edward "Rocky" Kolb, professor of astrophysics,
University of Chicago

The scientist does not study nature because it is useful to do so. He studies it because he takes pleasure in it and he takes pleasure in it because it is beautiful. If nature were not beautiful, it would not be worth knowing and life would not be worth living.

It is because simplicity and vastness are both beautiful that we seek simple facts and vast facts.

Henri Poincaré, mathematician and physicist

Acknowledgments

First and foremost I'd like to thank the physicists, engineers, computing professionals, technicians, and other support staff who had the vision and determination to make the Large Hadron Collider and its associated detectors a reality. The LHC is one of the most complex scientific endeavors ever attempted, and I have the greatest respect for a group of people who can make it all work. As the scientific results start coming in, and certain people become known as the "voice of the LHC," we should never forget the teams that designed and built this equipment. Without them, those voices would be forever mute.

I would like to thank Dan Claes for contributing several hand-drawn figures for the text. He has helped me out in the past and I am very grateful, as if I had included my versions of these figures, well, it wouldn't have been pretty. I'd also like to thank Barry Panas and Jeffery Mitchell for various computer-generated figures.

I'd like to thank Leon Lederman for his gracious contribution of the foreword. Leon is one of the greatest living particle physicists, with more than one discovery that would have nominated him to the Nobel club. He is also a tireless cheerleader for basic research and spends more time in retirement crisscrossing the country, speaking with the public and policy makers alike than most people do at the height of their careers. The Energizer Bunny's got nothing on Leon.

I am deeply indebted to my test readers, without whom the text would have been vastly less readable. Linda Allewalt, Drew Alton, Lee Blakley, Rebecca Messer, Frank Norton, Chuck Osborne, Mandy Rominsky, and Michael Walsh all made invaluable suggestions as to language, scope, depth and breadth.

I also asked several colleagues to check that I had not typed in a wrong number when describing all the equipment. This is very easy to do, as the as-built numbers of a complex technical project such as the LHC and its associated detectors are often somewhat different than the formal design documents. Marzio Nessi checked the ATLAS section, while David Barney checked the CMS description. Yves Schutz and Roger Forty looked over the ALICE and LHCb sections respectively, while Michael Koratzinos vetted the accelerator section. In addition, I'd like to thank James Gilles for helping to identify these experts, each with a talent for public communication and a willingness to help out.

I should like to thank Tim Tait for doing the theoretical fact checking for yet another book. As always, his careful attention to detail was very helpful in ensuring that the most important aspects of the various theories I discussed were mentioned. I remain in his debt.

Of course, it is no doubt true there remain some errors in the text, no matter how valiantly these people worked to find them. These remaining errors are solely the responsibility of Fred Titcomb, who by virtue of his irresistible and evil mind rays, forced me to keep in a few mistakes. Between you and me, Fred is unaware I am writing this book, but I've known him for over 35 years and he was a convenient scapegoat back in kindergarten. Since I assigned him responsibility for errors in my last book, it would be rude for me to not keep up the tradition and not blame him here as well. Sorry Fred!

I am grateful to Bruce Schumm, who made some important introductions.

I absolutely must thank the staff at the Johns Hopkins University Press, starting with the editor in chief, Trevor Lipscombe. At my request, he pushed through the manuscript review process in what must be record time to allow the book to come out coincident with the turn on of the LHC. I should also like to thank the initial anonymous reviewer, who turned around the book proposal in just a couple of days. Michele Callaghan did a wonderful job in editing the original manuscript, polishing off the many rough edges. I should also like to thank the design and production and advertising staffs at Johns Hopkins and the typesetter for their roles in making this book a reality.

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Prologue

Deep under the border between France and Switzerland, nestled between the primeval Jura Mountains to the north and the relatively youthful Alps to the south, a colossus stirs. When this giant fully awakens, it promises to reveal to mankind secrets long since lost to dim prehistory. The Earth has revealed ancient giants before. The nearby Jura Mountains lent their name to a period when Earth was stalked by beasts once long-forgotten: *Brachiosaurus, Stegosaurus,* and *Allosaurus.* But these denizens of the Jurassic era shook the Earth a mere 150 to 200 million years ago. The new awakening giant promises to teach us of a much earlier time, nearly 14 billion years ago. Indeed, it will tell us tales of the moment of creation itself. The giant stirring under the Swiss midlands is not a mythological beast but rather a scientific marvel, one of the wonders of the modern world. This book tells its story.

The CERN (the French acronym for European Nuclear Research Council) laboratory is one of the world's preeminent research institutions. Located just outside Geneva, Switzerland, it hosts physicists from all over the world who are working toward a common grand goal—unlocking the secrets of the universe. The centerpiece of CERN's research program is the world's largest and highest energy particle accelerator, designed to accelerate protons to nearly the speed of light and collide them in a controlled way. It began operations in 2008, with its full capacity coming online in 2009.

This accelerator has a name: The Large Hadron Collider, or LHC. Some two decades in the making, the goal of the LHC is to shed light on mysteries that so perplex those of us who think about what the universe is made up of and its origins: Why is the universe the way it is? How did we get here? Just what are the laws that govern the mass and the energy of the universe? Questions like these and many others are what drive physicists like me to dedicate our lives to seeking knowledge. These questions must have answers, which can be found if only we study them in the right way.

In this book, I hope to address these questions, and perhaps others, in five chapters. The first is a brief introduction into our current understanding of the universe and the particles that make it up. This understanding, while impressive for both its breadth and depth, is far from complete. The second chapter describes a handful of the most important questions that the LHC is intended to answer and, perhaps more critically, just *why* these questions are considered important. The third and fourth chapters are geared toward those interested in truly understanding how we intend to use this marvelous scientific instrument to solve the mysteries, with the third focusing on the accelerator itself and the fourth describing the four big particle detectors being built for the task. The fifth chapter will look at the broader physics frontier. While the LHC will no doubt be the premier facility in the world for the next 15 or 20 years, my colleagues and I are already looking toward the future. In this final chapter, I will describe the expected playing field after the LHC has told us what it can.

Before I begin to address these questions, I want to dispense with a misconception that periodically rumbles across the Internet and through the media. Some people fear that when the LHC commences operations, it will endanger the Earth. There is, however, precisely zero risk.

Some worry that the LHC might create microscopic black holes, cousins of the monster black holes created in the death throes of massive stars. Stellar black holes have a gravity field so strong they would suck all nearby matter into them, not letting even light escape. If the LHC's higher energy might actually manufacture micro black holes, and from knowing how their stellar brethren work, people have suggested that microscopic black holes might swallow nearby matter in a runaway reaction that would devour the Earth. And, as my son succinctly put it, "Dude, that would *so* not be good."

Other people worry about other perceived threats. Some fret that the LHC will forge a kind of matter called strangelets, which would radically alter the Earth's matter. Others have brought up the possibility of creating a vacuum bubble. Their fear is that the universe is itself unstable and the LHC might trigger the cosmos to fall into a more stable state, in which the laws of nature might be quite different and in which life is no longer possible. Yet another danger claimed is that the LHC might make magnetic monopoles, which some theories claim would make the center of atoms unstable and the Earth and all the people on it would essentially evaporate. There have been many seemingly worrisome ideas put forth that suggest the only logical thing to do is to be safe and not turn on the LHC at all; better safe than sorry and all that. However, each of these worries has one thing in common.

They are all totally unfounded.

It is *impossible* that any of these scenarios are true. Even more comforting, we can be assured that there are no other Earth-destroying dangers posed by the LHC, even ones we have not considered. This is an important point. I could describe the particular reasons why black holes are not a problem and mention things like Hawking radiation and so forth. But even if you accepted my explanation on why black holes are not an issue, a skeptical reader might not be reassured, since the real danger might be posed by strangelets, monopoles, or left-handed floptwiddles. To understand just how safe the LHC is, you need to hear an argument that works *no matter what the potential danger might be.* Luckily there is a persuasive argument. We know we are safe because you are reading this book. Let me explain.

To understand properly why there is no danger, consider two important facts. First, the LHC will indeed collide beams of particles with unprecedented energy and intensity. However, although scientists talk about beams of protons, every collision in the LHC will be between exactly *two* protons, one from each beam. While the intensity of the beams make it more likely that two protons will collide with high energy in any particular second, there is essentially zero possibility that any collision will involve more than two.

The second fact is that the Earth is constantly being bombarded by cosmic rays from outer space and has been since its formation about four and a half billion years ago. Cosmic rays from outer space are most often protons that have been accelerated to very high energy by mechanisms we don't need to understand here. What we do need to know is that the energy of these cosmic protons can be as high as *and even exceed* those in the LHC. These cosmic rays hit the Earth's atmosphere and experience exactly the same sort of interaction that they will in the LHC, with a proton from an atom in the atmosphere of the Earth hitting a high energy proton from space.

In the eons since the Earth was formed, Nature has repeatedly pounded the Earth with cosmic rays, generating more collisions than the LHC would produce in many millions of years. That's *millions* of years. Indeed the cosmic rays are not limited to hitting the Earth. The universe as a whole generates in a single second 10 million million times as many high energy collisions as the LHC will over the next decade. And yet we're still here. If there were any danger, we wouldn't. No matter what happens in the LHC, whether micro black holes, strangelets, or some other dangerous-sounding phenomena exist or not, Mother Nature herself has conducted this experiment millions of times already. So sleep well at night and look forward with me to the bounty of discoveries that the LHC is sure to uncover.

But, for now, we begin our journey to the quantum frontier.

1

What We Know

The Standard Model

Science is a way of thinking much more than it is a body of knowledge.

Carl Sagan

We humans know a lot about the world in which we live. The origins of this quest for knowledge predate writing, as early man's very survival depended on an intimate knowledge of the natural world of seasons and plants, of tools and fire. Sheer pragmatism required that humans be keen observers. Almost certainly, there were early thinkers who wondered about deeper mysteries: those who wondered Why? as well as What? and How? We will never know just how deep ran the thoughts of these early scientists; however, we do know for certain that by 2,500 years ago, people were asking thoroughly modern questions.

On their craggy peninsula in the Aegean Sea, the early Greek philosophers debated long and hard about whether the natural state of matter was resting or moving and whether there existed a smallest particle of matter. Just as important, they recorded their thoughts so that others, separated by both space and time, could appreciate and build on their ideas and debates. In the recording, they tacitly laid claim to the origins of fundamental science.

Much has been written of these long-dead thinkers, but this book is not concerned with their specific thoughts. After all, their ideas were only generally correct and wrong in many specifics. However, we *are* concerned with their intellectual legacy.

Although the early Greeks may be credited with the start of the journey, the picture has been clarified in the intervening centuries. Our mastery of the natural world includes curing deadly diseases, learning to fly, and taking the