String Theory and the Real World

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To my wife, Lois, who finds my physics life to be a grand adventure.

‘Some of us should venture to embark on a synthesis of facts, and theories, albeit with secondhand and incomplete knowledge of some of them—and at the risk of making fools of ourselves.’

—Erwin Schrodinger*, What is Life?* 1943

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Preface

My aim in this book is to explain why 'string theory' may provide the comprehensive underlying theory that describes and explains our world, perhaps fairly soon. Although such a claim might seem controversial to many, I hope to convince the reader that after progress in recent years this is now a defendable goal, and one deserving of broad encouragement. I also hope to convince the reader that not only are string theories about our world testable, but data will be essential to making the role of string theories compelling.

This book is not a systematic review, or a pedagogical explication. It is an enthusiastic, somewhat speculative, somewhat personal view of how compactified string/M-theories—plus data that may be reachable—seem to have the possibilities of leading to a comprehensive underlying theory of particle physics and cosmology, perhaps soon. The book is well founded on three decades of compactification research, and over two decades of compactifying M-theory, which is used as the main example because it is where my own work has focused. I will explain 'compactification' below. If string/M-theory is to be of any value in understanding our world it will be through compactified string/M-theories—this book is about them. The study of compactified theories is largely called 'string phenomenology'.

While the book is somewhat technical in places, I tried to explain topics so that any curious reader can see the point of technical aspects even if not the details.

It is necessary to use quotes around string theory, as above, because many things fall into the string theory domain, and most of them are not directly relevant to explaining our world. *String theorists study theories, not phenomena.* Much has been written or said in praise of, or criticism of, 'string theory'. Most criticisms apply to parts of string theory that are not relevant to explaining our world. For centuries the goal of physics was understanding the world we find ourselves in. Now that goal may be in sight via the combination of string/M-theory plus data from the Large Hadron Collider (LHC) and on dark matter, but sadly research aimed at that goal has largely been abandoned by string theorists. That is clear if one looks at the talks they have at conferences, at seminars at their universities, and in PhD theses.

How would we know if we had a theory that described and explained our world? We will see that we can make a list of about 30 questions and issues, such that if we had a single theory that dealt with all or nearly all of them we would be confident that our goal had been achieved. Experts would largely agree on that list, although of course not everyone would precisely agree. We will see that there is an example where most of the questions have been addressed, and answers to many of the questions and issues in that example have already been achieved. That may still be a long way from 'all', but it is very encouraging.

We know our world has a gravitational force, one that is classically well described by Einstein's general relativity theory, and that atoms and subatomic phenomena are well described by quantum theory. It has been known for about three decades that a mathematically consistent quantum theory of gravity can be formulated in ten (10D) or eleven space–time dimensions. We apparently live in four space–time dimensions. Therefore the full 10D or 11D theory of our world *must* be somehow projected onto the four space–time dimensions.

In fact, the serious physics study of having more than the dimensions we explicitly see began about a century ago with the Kaluza–Klein ideas aiming at unifying electromagnetism and gravity by writing the theory in a 5D world (four space and one time). I will describe this more in the book.

All of our analysis in this book will be for the case where the extra dimensions are curled up into a small space–time region of approximately Planck-scale size, a region that mathematicians call a manifold. Terms such as space–time, Planck scale, manifolds, etc will be defined later in the text. Such projected theories are called 'compactified string theories', compactification being the process that projects the ten or eleven dimensions onto four. Later we will focus on and provide examples for a particular one, compactified M-theory, since it has been well studied and has some successes.

Any research area that is called string theory or M-theory but is not compactified to four space–time dimensions is not relevant to the subject of this book. Its successes or failures have no relevance to this book. We will see that some compactified string/M-theories generically behave like good candidates for a final theory, and continue to do so as they are studied in increasing detail. There are a number of successes, some qualitative and some quantitative, and additional predictions, from compactified string/M-theories. I will describe some of them in this book.

On the other hand, what could be meant by testing a 10D theory in a 4D world without compactification? No one has given meaning to that notion. If anyone claims 10D/11D string/M-theories are not testable, ask them what they mean, or what such a claim could possibly mean, since experiments are performed in a 4D world.

When Shakespeare wrote, there was no understanding of the physical world we find ourselves in. Not one natural aspect of our world was explained. For reasons we probably understand, developments began about four centuries ago that led to our now having essentially a complete *descriptive* understanding of our world, of the world we see and of which we are all aware. Amazingly, there is nothing about the natural world known from before that era that is now taught to students, but there are a number of things learned and discovered soon after that time which are still taught [1]. It is important to distinguish a descriptive understanding from an explanatory understanding.

From what has been understood, we have also deduced some things about our world that we do not explicitly 'see'. Some such things are surprising and/or counterintuitive. Probably the most obvious is that the Earth actually orbits the Sun, even though it 'obviously' does not. We will discuss some additional counterintuitive aspects of our world as we go along. Probably the most surprising and important of those are the very strong arguments that we live in a world with more than three space dimensions. As already mentioned above, these arguments have been exciting for nearly a century, embodied earlier in Kaluza–Klein theory and then in modern string physics which began in the middle 1980s.

After four centuries of study, our grasp of the world we *see* is essentially complete. In order to say we understand our world, at least three things are necessary. First, we have to know what particles make up what we see, particles such as electrons and quarks (which are similar to electrons). We should understand what they are, why they are the ones, and why some others are not.

Second, we have to know what forces bind the quarks into protons and neutrons, binds protons and neutrons into nuclei, and bind the electrons to nuclei to make atoms. Three forces (electromagnetic, strong, weak) plus gravity account for our world. Again, why these forces, why not others? If we knew the particles but not the forces we would not be able to describe or explain what we see.

Third, we have to know the rules to calculate the effects of the forces on the particles. Classically, for understanding motion, the 'rules' are Newton's second law, $F = ma$. The modern formulation of the rules combines Einstein's special relativity and quantum theory into 'relativistic quantum field theory'. Relativistic quantum field theory was written about 1930. It has not changed since then, and is not expected to change, although understanding of it has greatly increased since then and continues to improve. There are strong arguments that the rules will not change. Newton's second law works for any force, and so does quantum field theory.

The combined knowledge of the particles, the forces, and the rules is called the 'Standard Model of particle physics'. It describes the world we see remarkably well. In its domain it is here to stay—it will not change. It was (essentially) completed by the discovery of the Higgs boson in 2012 at the LHC, at the European Laboratory CERN in Geneva, Switzerland. We will want to learn some aspects of the Standard Model as we go along in this book, but we will not need to know very much for our purposes. It is worth remarking that although it is called a 'model', the Standard Model is a full mathematical theory, the most complete ever written. The Higgs boson discovery is one of the most important scientific discoveries of the past century, because it points toward moving from a descriptive theory to an explanatory underlying theory that includes particle physics and cosmology.

There is also a Standard Model of cosmology. It includes Einstein's general relativity, and gives a good detailed description of a universe that first was of Planck-scale size with an unstable energy density that underwent an initial very rapid growth in size, an 'inflation'. After a short time the unstable energy density transitioned (the Big Bang) into a large number of energetic particles and some remaining energy density. The Universe has been expanding since then.

The Standard Models describe our Universe in terms of a relatively small number of parameters. It is very interesting to think about what we mean by 'small' here. In one sense the Standard Models are said to have about 20 parameters, such as the electron mass or the strength of the gravitational force, and 20 seems like a lot. Ultimately we hope to have a final theory with no adjustable parameters, or very few. Later in the book we will see how that can arise. Actually 20 is probably an exaggeration, because when we understand quark masses we will probably find that the theory of quark masses explains about seven of them simultaneously, so those seven should really have been thought of as one. Similarly, there are four force strengths in the 20, but if the forces are unified then probably those four are all determined at once.

On the other hand, historically physics was studied as a number of separate topics, such as motion, sound, waves, heat, thermodynamics, electricity, magnetism, and many more. Each of them was formulated so that it had a few input quantities, from which the rest of the phenomena in that area were calculated. The total number of parameters originally needed to describe all the phenomena encompassed by the Standard Models would give many tens, maybe hundreds—all the currently needed ones plus lots more that are now calculable in the Standard Models. So actually there has been great progress from the point of view of consolidating parameters. Even so, we expect (or hope) to eventually obtain a final theory of our world with zero or very few adjustable parameters.

In my view, we are living during a hugely exciting era for science, and for people more generally, one during which it may be possible to achieve a real understanding of our physical world, and the sense of dignity and meaning that could come along with that understanding. Two things are crucial for that to be so, one experimental and one theoretical—either alone would be less exciting.

First, experimentally, the facility at the European Laboratory CERN called the LHC that collides beams of protons to create new particles is finally taking data at energies and event rates where well motivated theories suggest new particles may be observed that point to how to formulate the underlying theory. Some people might say such claims have been made or could have been made in the past. The difference is that now the claims are based on calculations in actual theories, while in the past they were based on analogies or 'naturalness' arguments. More broadly, the Standard Models do not leave descriptive gaps or puzzles. Additionally, it was learned in the 1980s that dark matter should be composed of new forms of matter, not of the atoms from which we are made. Finally after over three decades of development detectors are beginning to operate that are sensitive to most hypothetical forms of dark matter in realistic amounts, and new ones are being designed to cover any regions that cannot yet be searched. Earlier dark matter detectors might have detected the dark matter (or part of it). Searching for dark matter is now a mature area.

Without the LHC, a facility supported regionally but not by any single country, and the dark matter detectors developed recently, and perhaps the next generation of dark matter detectors, we might never have the data to confirm an underlying theory. Of course it may be that the needed discoveries will not be made, but at least we know we are in the region where optimism is reasonable and defendable. No amount of cosmology or astrophysics could tell us how to extend the Standard Model, or what the dark matter is.

Actually, the situation today is surprising to many because almost all the data are in, so to speak. We know: the Universe is long-lived; there are three large space dimensions; the amount of dark matter; the size of the matter asymmetry of the Universe; the Universe is geometrically flat to high accuracy; the dark energy equation of state is essentially unity; the size of the cosmological constant; that the rules of quantum theory hold; that an effective theory of inflation gave an accurate description of data including the measured high scale of inflation, the tensor modes and small but non-zero non-Gaussianities; electron and neutron electric dipole moments are surprisingly small; there are three families. Quark and lepton masses, and soon even neutrino masses, and the Higgs boson mass and decay branching ratios are approximately measured and soon will be accurately measured. Even though several of these items are technical, the reader can see the point that most of what we need to know is known. The two big gaps are what particle(s) make up the dark matter, and whether there is electroweak-scale supersymmetry.

For historical reasons CERN has a long-term treaty-based budget from member countries, rather than annual fluctuating funding, so eventually CERN may go to new levels of intensity or energy. China has begun to discuss building a more energetic collider without requiring help, which would be a wise decision for several reasons for a leading country. While the costs are large, the investment would be paid back many times over in economic and human returns. An international R&D program is underway to plan a circular proton–proton collider whose energy is about 100 TeV, over seven times that of the LHC. Calculations imply that such a collider could make important discoveries. The goal is to have a ‘conceptual design report’ that would be a basis for proceeding by the end of 2018.

Dark matter detectors, while not inexpensive, are being built by several countries. Again the investment would be well rewarded in economic terms, even without discoveries. Dark matter detectors are rather specialized so several kinds may be needed. As we will see later, for dark matter there is currently little theoretical guidance. Altogether, on the experimental side we have good scientific arguments that the discoveries needed to confirm or disprove the theories might be possible in coming years. However, if we had all the data but no theory, we would not know what the data implied.

The string theory framework has all the richness and structure needed to provide an underlying theory. It is easy to misunderstand what that statement means—a significant part of this book is devoted to explaining that. It is remarkable that Michael Green and John Schwarz figured out in the mid-1980s that to have a mathematically consistent quantum theory of general relativity describing a world meant having a world with nine space dimensions. When the extra dimensions are curled up into a Planck-scale size manifold the resulting compactified theory generically behaves like one with strong, electromagnetic, and weak forces in addition to the gravitational force described by general relativity. The resulting theory behaves like the theory that has increasingly been formulated piece by piece over the past century. It is a coherent, consistent theoretical framework that addresses all the basic questions physicists and cosmologists have wanted to ask about our world. Much has been written about the testability of string theories—we will see that *compactified* string/M-theories are indeed testable in the traditional way of physics theories, contrary to what is being said and written in a number of journalistic articles, blogs, and books.

There is some research on purely gravity-based theories, so-called loop quantum gravity, or emergent gravity. Because such work intrinsically does not have any connections to the other forces, or to the particles, we will not consider it further in this book. That the string/M-theories address all these aspects simultaneously is one of their important strengths.

Several exciting features arose as the resulting theoretical framework from compactified string/M-theories was studied over the past three decades. The Standard Model is a special kind of quantum field theory, called a Yang–Mills gauge theory. It turns out that compactified string/M-theories generically are such theories. In addition it turns out that compactified string/M-theories also contain states with properties like those of massless quarks and leptons, again a property of the Standard Model (before the Higgs physics plays its role and allows small masses). These are powerful tests of string/M theories. The compactified string/M-theories could only describe the real world if they had these properties, and they do, so they have passed powerful tests already. Ultimately a particular Yang–Mills gauge theory with the Standard Model particles and forces must emerge if this approach is valid. The situation today is encouraging, although of course not guaranteed to succeed.

Supersymmetry is a hypothetical property of an underlying theory, a very desirable one. It has a number of attractive features, one being it allows connecting the Planck-scale ideas with the Standard Model. Whether nature is indeed supersymmetric should be testable at the LHC, and is probably the most exciting goal of LHC data in the coming years. It would be discovered via observing some new particles related to Standard Model particles (superpartners). People had hoped that such discoveries would already be made, based on naïve reasoning (called 'naturalness') rather than serious calculations, but superpartners have not been found so far. That has led to superficial claims that nature is not supersymmetric. Actually, LHC is just entering the well-motivated region of energy and intensity where compactified theories imply the superpartners should exist. That was not known before a few years ago. We will examine this situation in the book.

Another new feature that emerges from compactified string/M-theories is particles called 'moduli'. They can be thought of as quanta of the fields needed to describe the curled up dimensions. With six or seven small dimensions a description requires specifying their sizes, relative orientations, etc, so a large number of moduli. The moduli quanta behave like unstable particles and affect cosmological history. They are an interesting new aspect of the Universe that emerges from the quest to have a quantum theory of gravity. Without studying compactified theories we would probably not know about them.

String/M-theories have many solutions, which has led to the notion of a 'landscape' of universes. Some people have been concerned about how we could find a solution that described our world if there were very many to examine. Since most string theorists do not focus on compactified theories, which we have seen already are very much like our world, they are confused about this question, but it is not a problem, as we will see. Since the compactified theories generically are like the Standard Models, it is not hard to find good candidates. Another subtlety about the landscape is that many of the solutions will not be populated universes—e.g. they will only live very short Planck-scale times. This has been studied a little, but its implications are not yet understood.

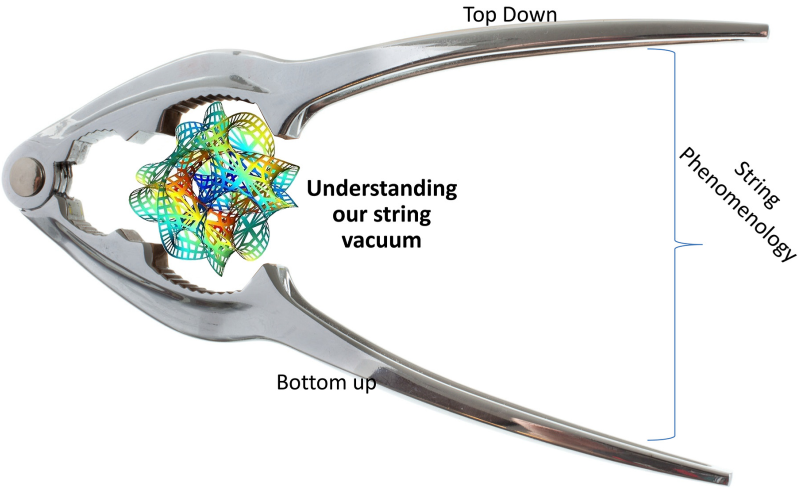


Figure P.1. This figure illustrates that getting at the physics and predictions and tests in the curled-up dimensions requires both a top-down (theory) approach, and a bottom-up (data, phenomenology) approach. With either one we cannot expect to crack open the (here, projected Calabi–Yau) manifold shown as the nut (drawn by Andrew Hansen), but with the combined approaches we can.

Today both the experimental and the theoretical parts of our quest for extending and deepening our comprehension of our Universe are ripe for fruitful progress. Either without the other is unlikely to take us to a new stage; with both good progress is possible, perhaps likely. Figure P.1 is an image that I hope will easily come to people's minds. The object about to be cracked is a projection based on a Calabi–Yau space (provided by Andrew J Hansen of University of Indiana). If only the bottom arm of the nutcracker (data and phenomenological theory) is used it will not crack open the 6D object so we can get at the underlying physics and theory. Similarly if only the top arm is used without the bottom (string theory) it will not be possible to get at the underlying physics and theory. But if both are used it is at least possible, and perhaps now probable.

In order to keep most parts of the book as self-contained as possible, I have not worked to edit out redundancy. While some of the book is rather technical, the reader can obtain the sense of the arguments without trying to grasp the technical aspects. Some are in square brackets [...] as a warning to avoid them.

Since this book is meant to present a point of view rather than a review, or to be a balanced presentation, it will have few references. Since compactified M-theory is emphasized because it has been my focus, some references to its early history will be included. Otherwise a few references will be given to help anyone who wants to find further information. I apologize to many people who would have been referenced in a review, and I hope they understand the role of references in a book such as this.

I am very grateful to Professor Bobby Acharya, at King's College London, with whom I have collaborated for a decade in this area, who has taught me a great deal, and without whom the work would not have been done. I also want to thank a number of colleagues for collaboration and/or discussions: Konstantin Bobkov, Sebastian Ellis, Daniel Feldman, Joel Giedt, David Gross, Eric Kuflik, Piyush Kumar, Ran Lu, Brent Nelson, Malcolm Perry, Aaron Pierce, Jing Shao, Kuver Sinha, Diana Vaman, Scott Watson, Bob Zheng, and Anna Zytkow.

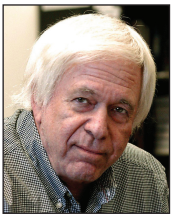
Finally, I want to repeat and emphasize that compactified string/M-theories are strong and testable candidates for theories that provide a comprehensive underlying theory that describes and explains our world, incorporating the Standard Models of particle physics and cosmology. The purpose of this book is to explain and document that statement. The compactified string/M-theory perspective can change how we view the world in a number of ways.

Reference

[1] Margolis H 2002 *It Started with Copernicus* (NewYork: McGraw-Hill)

Author biography

Gordon Kane



Gordon Kane got his PhD at University of Illinois. He joined the University of Michigan in 1965, and became Professor of Physics in 1975. He is now Victor Weisskopf Distinguished University Professor of Physics, and Adjunct Professor in the School of Art and Design. He was Director of the Michigan Center for Theoretical Physics from 2005–2011. In 1971–72 he was a J S Guggenheim Fellow at Rutherford Laboratory and Oxford, in 1986 Scientific Associate at CERN, and in 2007 he was Member, Institute for Advanced Study, Princeton. He has been elected a Fellow of the American Physical Society, Fellow of the American Association for the Advancement of Science, and Fellow of the British Institute for Physics. He was awarded the 2012 Julius Edgar Lilienfeld Prize of the American Physical Society, and co-awarded the 2017 Sakurai Prize of the American Physical Society. He was a 2009 Member of the Triennial Committee of Visitors of the National Science Foundation and Chair of its Theoretical Physics Subpanel, and has served on the High Energy Physics and Scientific Advisory Committees at the Stanford Linear Accelerator Center and at Brookhaven National Laboratory. He originated and co-organized an International Summer School in String Phenomenology, at Simons Center in 2012.

Gordon Kane's research has covered several areas of physics beyond the Standard Model(s) of particle physics and cosmology, including supersymmetry, Higgs physics, dark matter, cosmology, collider physics, and string phenomenology. He has published over 200 scientific papers, given over 250 scientific talks, and written or edited ten books. Two are for the general public, in particular *Supersymmetry and Beyond, from the Higgs Boson to the New physics*, Basic Books 2013.

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String Theory and the Real World

Gordon Kane

Chapter 1

Introduction: the Standard Models

In recent decades the boundaries of the goals of physics have changed. Starting in the 1970s with the development and confirmation of the Standard Model of particle physics, the discovery of the idea of supersymmetry, and approaches about unification of the electromagnetic, strong, and weak forces of nature, and then greatly encouraged by the discovery of inflation and of string theory in the 1980s, previous limits began to be ignored. For the first time in history, physicist's thinking began to include the possibility of a unified, underlying comprehensive theory of the physical world, a final theory based on publishable physics research, not on philosophical speculation. That is not to say that there is already such a theory—there is not—but that increasingly many physicists began to take seriously the possibility that the ingredients needed to achieve such a theory might be already or soon available rather than at best a goal for the distant future. I will argue here with concrete and detailed examples that is indeed the case. I will even argue that we may be much closer to achieving a final theory than is recognized by many workers, even those close to the subject.

As described in the preface, if we want to achieve an understanding of the physical Universe, at least three things are necessary: we must know the basic constituents everything is made of, the particles; we must know the forces that bind the constituents to form our world; and we must know the rules to calculate the results of the forces acting on the constituents. Historically the rules came first. The rules are the Einstein's special relativity plus the quantum theory, combined by 1930 into relativistic quantum field theory. Quantum field theory is a framework that holds for any forces and particles. During the second half of the twentieth century the particles and forces were identified.

The particles that form all we see are the familiar electron, and two more called quarks (named the up quark and the down quark, for a reason). Quarks are like electrons, but carry an additional charge (called the 'color charge') so they feel an

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additional force (the 'strong force' or 'color force'). The use of the word 'color' is an analogy; there is no connection to real colors. The up and down quarks bind to make protons and neutrons, which have no net color charge. Protons and neutrons bind into the nuclei of the chemical elements via a residual leakage of the color force, called the nuclear force. Electrons bind to nuclei via the electromagnetic force, making atoms. Atoms are neutral but bind via a residual leakage of the electromagnetic force into molecules. Molecules form flowers and espresso and people and planets and stars, and all we see.

This picture is fully quantitative and the results are calculable at all levels. It is the simplest description ever to emerge, simpler than the attempts of the Greeks or other cultures, such as earth, air, fire, and water.

The quanta of the electromagnetic force that bind electrically charged particles into atoms and molecules are photons, and the quanta of the color force that bind colored particles into hadrons are gluons. Essentially all the quarks and electrons in everything we see were created in the Big Bang. There are several other quarks, and other particles like electrons, and more particles, but they do not enter directly into what we see.

Four forces are necessary and sufficient to form the particles into the world we see. The Standard Model incorporates the electromagnetic, strong, and weak forces in a fully relativistic quantum field theory. Classical gravity is attached.

Particles have another property, called spin. In quantum theory spins are quantized, so they can have spin 0, 1/2, 1, 3/2, 2, all in units of Planck's constant. Physical theories with larger spins do not occur. In quantum theory spin is analogous to angular momentum, but not precisely. In practice we will not need to do more with spin than be aware of it being a property of particles. Particles with integer spins are bosons, and particles with half-integer spins are fermions. For individual particles their behavior is not particularly different if they are bosons or fermions, but two or more that form a system do behave differently. That will not affect us except indirectly as to whether axions form dark matter. Supersymmetry is a symmetry of the theory under which bosons and fermions in the theory are interchanged. Matter that we see is made of fermions, while the bosons mediate the forces.

The theory called the Standard Model of particle physics is an awesome theory. The name 'Standard Model' is of historical origin, and is misleading in that the Standard Model is the most mathematical theory known. It describes the world we see, and explains much of what we see. It achieves the goals of physics since its modern beginning four centuries ago. The Standard Model is very well tested, and in its domain it is here to stay. To honor it we capitalize its name. A textbook written now on the Standard Model will never have to be updated.

We add the Standard Model of cosmology to that of particle physics. We know rather well what comprises the Universe: about 5% is the matter we see and are composed of, mostly in the form of atoms. About 25% is dark matter, some sort of particles that clump under gravity as normal matter does, but do not form stars and emit light. We do not yet know what the dark matter particles are, although we know a lot about what dark matter is not.

About 70% of the Universe is called ‘dark energy’ and does not behave as matter under gravity but has a uniform density throughout the Universe. This part is effectively a force that causes the expansion of space–time at an increasing rate. A small amount is radiation (photons)—about a part in 100 000. Some is neutrinos, about 0.5% or a little more.

There is also a standard cosmological history. There is good evidence that at an early stage the Universe was an unstable energy density, which inflated from a Planck-scale size to a size perhaps of the order of a soccer ball very rapidly, an increase in size of a factor of about 10^{35}! Then it decayed into energetic particles, in what we call the Big Bang. The history usually assumed (called a thermal history) is that after the Big Bang the energy density of the Universe was dominated by photons since most particles decayed or annihilated into photons fairly quickly (‘radiation dominated’). It simply expanded and cooled. We will see that compactified string theories imply instead a non-thermal cosmological history—this is one of the generic predictions of compactified string/M-theories.

The Standard Models together describe an amazing amount, but are actually incomplete at a conceptual level. It is helpful to state three ways they are incomplete, although the three are somewhat related. They are:

1. Some questions or phenomena have no Standard Model answers or are not described by them. For example: why are there more families of particles like up quark, down quark, electron (and electron neutrino), and why are there apparently precisely three such families? The additional families seem to play no role in the behavior of our Universe; their role must somehow arise in the underlying theory. The Universe has a matter asymmetry, with about a billion times more matter than antimatter. At the Big Bang one would expect the initial state of pure energy to turn into equal amounts of matter and antimatter. How does the matter asymmetry originate? What is the physical inflaton that increases the size of the Universe such a huge factor during inflation? What is dark matter? Why does the strong force (quantum chromodynamics (QCD)) not have interactions that violate the conservation of charge parity (CP, the product of charge conjugation and parity transformations) even though such interactions are fully allowed in principle? The Standard Model *cannot* answer these questions and others; it is not that we have not yet figured out the answers in the Standard Model.
2. The Standard Model is a descriptive theory. It does not explain why its particular electroweak and color forces are what they are, and whether they are inevitable, or why the constituents are quarks and electrons instead of some other particles, or why the CP symmetry is slightly broken rather than conserved. One can extend the list of such ‘why’ questions.
3. The Standard Models are effective theories. Fortunately, much of the physical world can be divided into isolated domains that can be studied separately, each called an effective theory. That is why physics is the easiest science. The physics of atoms assumes relativistic quantum field theory, the electromagnetic force, the existence of electrons and nuclei with specific masses and charges and spins, and then deduces everything in its domain.

> For understanding atoms we do not need to know about quarks, or stars, or anything else. The Standard Model inputs quarks and leptons and their masses, the Higgs physics, the four forces (attaching gravity) and their strengths, and the rules of quantum field theory, and then deduces the existence and properties of protons, nuclei, atoms, stars, and so on. It does not need to know about inflation. If a theory has inputs it is an effective theory. Eventually we hope for a theory without inputs, which can be imagined. One way this is relevant is the hierarchy problem.

Some workers in these areas think that physicists will be able to answer all such questions about our world, and will replace descriptions with explanations and deeper understandings, greatly reducing the incompleteness. Some workers with such views expect that the answers and explanations will emerge from one comprehensive underlying theory, a theory we can call the final theory (following Steven Weinberg). This optimism arises from the situation with current and past research and ideas, and with the newest experimental facilities. The optimism is useful because it leads people to work hard on the relevant research. Of course, the quest may not succeed. Perhaps we will obtain an 'almost final theory' that leaves one or two questions or issues unsettled. If no final theory (or almost final theory) emerges, eventually people will concede that and largely lose interest.

Many experts who specialize in various aspects of string theory will not endorse the possibility that the final theory of our vacuum may be soon forthcoming, because they work in technical areas that lack overviews. Anyone who focuses on solutions in other than four dimensions, or black hole solutions, or anti-de Sitter space/CFT, or amplitudes, or higher spin theories, or dualities, or holography, or moonshine, or many other areas will have no reason to expect a comprehensive theory to emerge. And of course solutions can be constructed that do not describe our vacuum. Similarly, experts in QCD physics or Large Hadron Collider (LHC) physics or dark matter physics will not have an overview of the ingredients described below, and generally will not be aware of the emerging final theory opportunity. Some who are not aware of it will be skeptical about it.

In this book we focus on how we can recognize if the quest might be successful. How will we test it? First we discuss the issue of testing theories in physics in general, and clarify some aspects. Then we describe several ingredients that seem necessary for progress, such as the idea of supersymmetry. Next we give a list of questions that should be answered by a final theory. This is interesting, and people like looking it over and checking it against their ideas and goals. We will illustrate reasons for optimism by giving an example where the majority of the questions are already answered in one theory, compactified M-theory, and describe a number of its tests.

Those who do work toward a final theory typically have done so via a 'top-down' approach. They imagine writing a ten-dimensional (10D) string theory, finding that some principle leads them to a particular compactification to four dimensions, and a particular vacuum state. It would be fine if that worked, but so far it has not been a fruitful way to proceed. That is not surprising since historically physics has always been driven by both theory and data. In addition, if any crucial aspect of data, or any concept, is missing, progress can be greatly slowed. What works well is what I have called the nutcracker approach (see figure P.1 and its caption). If the end result is viewed as cracking open the underlying structure, then both the top-down and the bottom-up (data driven phenomenology) approaches will be needed.

If all the ingredients are in place, progress can be quite rapid. We have a good and relevant example of that with the Standard Model of particle physics. At the beginning of the 1970s people spoke disparagingly of the status of particle physics. But with the improved understanding of non-abelian gauge theories, plus the already existing data and theoretical structure, the whole picture fell into place and by 1973 the full Standard Model existed. It is arguable today that we are in a similar situation, with the missing ingredients being both experimental (confirmation of supersymmetry and learning what the dark matter is) and moduli stabilization plus supersymmetry breaking in compactified theories (explained later). The LHC is now working in a region of energy and intensity where well-motivated theories imply superpartners could be seen by late 2018. Given the ingredients listed here, one can defend the point of view that with the discovery of superpartners and identification of dark matter a final theory of our vacuum could emerge quickly, with the data pointing to the appropriate detailed theory.

Einstein spent most of the last two-thirds of his research career searching unsuccessfully for a unified description of the gravitational and electromagnetic forces. In hindsight we understand that his search could not have been successful, because he did not try to include unifying with the weak and strong forces as well, and because he did not know about quarks. A comprehensive unified theory would have to include several essential parts in order to work. It would have to be a relativistic quantum field theory in four space–time dimensions. It would have to include the particles and forces of the Standard Model of particle physics, and general relativity.

Another necessary ingredient came well over a century ago. With the invention of quantum theory, Max Planck realized that physicists had discovered the three fundamental constants of nature needed to make universal units, the so-called Planck scales (explained below). A final theory would need to be formulated at length and energy and time scales that were universal and independent of people or accidental features. With the proportionality constant for force in Newton's law of gravitation, and the speed of light that emerged from Maxwell's equations, and Planck's quantum scale, it became possible to express any quantity having units in terms of these three quantities. One could imagine a theory having a simple set of equations expressed in Planck units. This is explained in more detail in the next chapter.

Supersymmetry is another crucial ingredient, because it allows formulating a theory at the Planck scales while the same theory implies phenomena at the scales of our vacuum, where protons and nuclei and atoms can exist and form our world. With supersymmetry different scales can exist at stable separations. The idea of supersymmetry is well formulated, but not yet explicitly confirmed experimentally. There is good reason, based on theory, to think discovery of the superpartners of Standard Model particles should occur at the CERN LHC in the next few years. Without technological societies and institutions that pursue fundamental research goals and fund them at the very high levels needed, the supersymmetry ingredient might never be tested. Once supersymmetry was formulated its absence would not have blocked formulating a final theory, but without the actual discoveries important tests would be lacking, and fewer people would be convinced the theory indeed explained our world.

The final crucial ingredient was string theory. What is string theory? What is any theory? The main goal of physics has been to understand the physical world. That means writing a consistent mathematical theory that describes the physical world, and understanding why that theory actually describes nature. Historically one writes effective theories that increasingly encompass larger areas, integrating ones that cover smaller domains. Each effective theory has some inputs and derives others. Eventually we hope for a comprehensive one that has no, or almost no, inputs.

An important and subtle point is that discoveries push thinking toward some directions and away from others. Then more people focus on the better approach, and progress is amplified.

Given our world, it is essential that the final theory include a relativistic quantum theory of gravity. In 1985 Michael Green and John Schwarz showed that mathematical consistency required that such a theory, one that could also describe quarks and electrons, have nine space–time dimensions. In that theory the basic objects would not be point-like as in quantum field theory, but extended. They could be stringy, e.g. extended in one dimension, or more complicated. Stringy objects are the simplest case, and much of the mathematics of stringy objects had already been studied, so that quickly became the default. A decade later Edward Witten showed that a related approach called M-theory implied 11 space–time dimensions.

String theories provide a fruitful opportunity for much study. Obviously, in order to provide a framework for an underlying theory for our world, string/M-theories must be projected onto four space–time dimensions, a process called ‘compactification’. The projection is naturally achieved by making the other dimensions Planck-scale size. When that is carried out, one might worry that information is lost. On the contrary, remarkably it turns out that the resulting theory has not only gravity, but also the electromagnetic, weak, and strong interactions. In addition the basic string massless states can be interpreted as quarks and electrons, and as the particles that mediate the forces, photons and gluons, and the W and Z bosons of the weak force. Relativistic quantum field theory fails to provide a quantum theory of gravity for point-like particles. Treating particles as points is too singular. Probably any way of giving them extension would work; strings are just the simplest case.

Sometimes one reads descriptions of string theory and particles as vibrating strings. While correct, that is actually not helpful. The particles we know are all massless in the string theory, and differ because they come in representations of symmetries. For example, there is an up quark and a down quark that come together in a doublet of the electroweak theory. When they vibrate the energy of the vibrating string is very large, close to the Planck mass, so it does not affect our world very much. In the string/M-theories all the Standard Model fundamental particles (quarks, leptons, W and Z bosons) are massless. Then they obtain mass because of the Higgs mechanism, which works so that photons and gluons stay massless. The

Higgs mechanism works in such a way so that the theoretical properties that implied massless particles remain in place, but the solutions are allowed to violate it. This is called spontaneous symmetry breaking.

The basic point that theories have solutions whose properties can be very different from the properties of the theories can be explained simply and generally. Suppose a theory is stated in terms of an equation, $X \times Y = 16$. For simplicity consider only positive integer values of X, Y as solutions, and assume that interchanging X and Y gives the same solution. Then there are three solutions, $X = 1$ and $Y = 16$, $X = 2$ and $Y = 8$, and $X = Y = 4$. What is important is that the theory ($XY = 16$) is symmetric if we interchange X and Y, but some solutions are not. The most famous example is that the theory of the Solar System has the Sun at the center and is spherically symmetric, but the planetary orbits are ellipses, not symmetric. The spherical symmetry of the theory misled people to expect circular orbits for centuries. Whenever a symmetric theory has non-symmetric solutions, which is common, it is called spontaneous symmetry breaking.

In this example above, as often in nature, there are several solutions so more information is needed, either theoretical or experimental, to determine nature's solution. We could measure one of X or Y and the other is determined. Improving the theory leads to an interesting case. Suppose there is an additional theory equation, $X + Y = 10$, also symmetric if we interchange X and Y so the theory remains symmetric. But now there is a unique solution, $X = 2$, $Y = 8$, and it is *not* symmetric. In fact, there are no symmetric solutions. Via the Higgs mechanism all the massless fundamental states except photons and gluons are allowed to be massive even though the theory invariances remain valid.

String theory does not yet have a rigorous definition. Sometimes people state that as a problem or criticism, and some suggest that is a reason not to take string theory seriously. They are unaware or have forgotten that historically the development of theories has always been haphazard. Some results are obtained, and after a while they are understood better, and finally formalized. That is true of Newton's laws, where solving the 'action-at-a-distance' issue took two centuries. It is true of quantum theory, where its formalization started to emerge within a decade of the initial successes, and is still ongoing research. It is true of evolution where the Mendelian genetics underlying heredity were unknown when Darwin wrote. This sort of criticism of string theory is basically irrelevant to understanding our world.

Today it is possible for the first time to address all the basic questions about laws of nature and the Universe and its history scientifically. The Standard Model is exciting because it summarizes four centuries of physics and tells us how the world works. Supersymmetry is exciting because it provides the opportunity to combine the Standard Model and string/M-theory and have a window to the Planck scale. String/M-theory is exciting because it provides a framework that addresses how to explain the Standard Model particles and forces and their properties, and to connect them with gravity in the framework of relativity and quantum theory. Being exciting does not guarantee that nature will behave that way, but we should commit ourselves to finding out if it indeed does behave that way. We should take the theories more seriously.

Full list of references

Prelims

[1] Margolis H 2002 *It Started with Copernicus* (New York: McGraw-Hill)

Chapter 2

[1] Kane G 2013 *Supersymmetry and Beyond* (New York: Basic Books)
[2] Planck M 1991 *The Theory of Heat Radiation* (New York: Dover)

Chapter 6

[1] Witten E 1995 *Nuclear Physics* B **443** 85–126
[2] Papadoupoulos G and Townsend P 1995 *Phys. Lett.* B **357** 300
[3] Acharya B 1999 *Adv. Theor. Math. Phys* **3** 227
[4] Acharya B and Witten E 2001 arXiv: hep-th/0109152
[5] Beasley C and Witten E 2002 *J. High Energy Phys.* JHEP07(2002)046
[6] Lukas A and Morris S 2004 *Phys. Rev.* D **69** 066003
[7] Acharya B, Bobkov K and Kumar P 2010 *J. High Energy Phys.* JHEP11(2010)105

Chapter 7

[1] Honecker G 2016 arXiv: 1610.00007