IOP Concise Physics

String Theory and the Real World

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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

doi:10.1088/978-1-6817-4489-6ch1

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.