NO EXPERIMENT DISAGREES WITH STANDARD THEORY PREDICTIONS

All the preceding experimental tests confirmed the Standard Theory, or participated in establishing it. A result that is perhaps as important as any other is that no measurement disagrees with the Standard Theory predictions, though many could have. There are two possible kinds of disagreements. One is the occurrence of phenomena not predicted by the Standard Theory, such as a new particle (see Chapter 10 for examples) or the decay of a proton (see Chapter 5). Rather than a failure of the Standard Theory, these would be welcome clues telling us how to extend the Standard Theory. The other would be a contradiction of the internal structure of the theory. For example, if different experiments had given markedly different values of θ_W, or if quark jets had not behaved as spin 1/2 particles, or if different Z^0 decays had occurred in the wrong proportion, or if dozens of other things had happened, then the Standard Theory would just be wrong. None of the latter has happened. If the top quark were not detected at Fermilab, the Standard Theory would have been wrong.

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What Do Physicists Mean by "We Understand"?

Since we know in principle how to calculate the behavior of atoms, we can say we understand atoms. But if we have to just take the value of the electron mass as measured, rather than derive it, and since the value of the electron mass affects the properties of atoms, there is a sense in which we do not fully understand atoms. If we analyze what "understand" means, we can clarify how to describe how much understanding we have.

Levels of Understanding

In order to explain what has been accomplished in particle physics, and the aims of current research, I have found it useful to distinguish three levels of understanding. The first and most familiar level can be called Descriptive Understanding. Two further levels, which I call Input and Mechanism Understanding and Why Understanding, help considerably to clarify the meaning of "understanding." Both are rather subtle, somewhat special to particle physics, and both are hard to find analogies for. The criteria for Input and Mechanism Understanding are especially unfamiliar ones.

Perhaps an imprecise analogy would be useful to illustrate the distinctions among the levels of understanding. If the world is a videocassette recorder (VCR), and we can work the VCR well and do everything with it that it is capable of, then we have a Descriptive Understanding. Of course no documentation came with it—experimentation was essential to learn. But at this level we don't understand it well enough to fix it if it is broken. Input and Mechanism Understanding would mean we could repair it without outside help or parts. Why Understanding would mean we could invent the idea of a VCR and design it and make it from raw materials without outside help. Clearly, Why Understanding ~~is really~~ vastly more difficult than Input and Mechanism Understanding.

Level I—Descriptive Understanding

A subfield or area of science (for example, particle physics, atomic physics—the study of atoms, microbiology) has attained a Descriptive Understanding of its subject matter if it is possible to give a complete and well-tested description of how things work in that subfield. It is necessary to be able to correctly predict the results of experiments, or at least be able to interpret experiments after they are done if the measurements involve too much complexity to carry out a calculation ahead of time. For example, Newton provided a Descriptive Understanding of motion and of gravitation, because with his laws it became possible to take various inputs such as masses and then describe the motion of all objects. With the Standard Theory, particle physics has achieved a Descriptive Understanding of its entire domain, as have some other subfields of physics.

Descriptive Understanding in particle physics requires knowledge of three kinds that we first met in Chapter 2 from the historical point of view, and then in Chapter 4 as a way of

organizing the Standard Theory. First, to understand what we are made of, we must know what *constituents* are found when we subdivide matter into smaller and smaller pieces, and we must have good arguments that even smaller subdivisions are not possible. Of course, we can never prove that smaller subdivisions will not be found if a future supercollider can probe to smaller distances. But we have seen that matter has already been probed to distances far smaller than where structure might have occurred, so perhaps we do know the final constituents.

Second, we must know the *forces* that act on the constituents to bind them into the structures we encounter—quarks into protons and neutrons, protons and neutrons into nuclei, nuclei and electrons into atoms, atoms into molecules, molecules into us.

Finally, we must know the *rules* to use in order to calculate how the constituents interact under the influence of the forces, as described in Chapter 4. Einstein's special relativity and the quantum theory are the modern form of the rules. Since the 1920s the rules for calculating have not changed in principle, though there has been tremendous improvement in understanding how to use them.

The progress of recent decades has been in learning what the constituents and the forces are. Before the 1960s the electron was known, but there was no idea what the other basic constituents could be. Before the 1970s the electromagnetic and gravitational forces were known, including the proper expressions to use for them in Newton's law or the Schrödinger equation of quantum theory. The existence of the weak force was also known, but there was no understanding of what to put into the rules to calculate its effects. The existence of the strong force was unknown, though hinted at by the existence of one of its manifestations, the nuclear force. Today the situation is totally different—the Standard Theory satisfies all the conditions for a full Descriptive Understanding.

Level II—Input and Mechanism Understanding

The second level, Input and Mechanism Understanding, is the least familiar one. It arises in the sciences, where the Descriptive Understanding is mathematical. To achieve this level it is necessary to recognize the mechanisms for how things work, which can include knowing how symmetries of the theory are broken (an example is given later in this chapter), or knowing which solution of an equation describes a system (see examples below). Input and Mechanism Understanding also requires that no masses, constants, or parameters be inputs taken from measurement or other subfields; they must be derivable from the theory of the subfield itself. Inputs (such as masses or force strengths) are not the same as mechanisms, so one could speak of an Input Understanding or a Mechanism Understanding, but their logical status seems to be the same, and sometimes they are connected (as with the Higgs mechanism and masses explained in Chapter 8), so probably they should be thought of as the same level of understanding.

For example, consider Newton's law of gravitation, which says that any two bodies are attracted to each other in proportion to the product of their masses. Many people asked what was really happening to cause the attraction—what was the mechanism? Newton did not know, nor did anyone else for over two hundred years. A Mechanism Understanding was not achieved until after the notion of a field was elucidated by Faraday and Maxwell in the nineteenth century, and finally Einstein showed that changes in the field (because of particle motion) travel at the speed of light. Then the "action-at-a-distance" problem was resolved, and the mechanism by which gravity worked was understood: A field is established by every massive body, and when it moves the field configuration propagates out from the body throughout space at the speed of light; any other massive body feels the field and is attracted.

When I was taught atomic physics and quantum theory, the approach was that we were given electrons and nuclei with certain masses and other properties, and a force acting between them with a strength characterized by the size of the electric charge on each. The problem was to calculate the properties of atoms, such as their energy levels, various experimentally observable rates, the colors of light they emitted, and so on. All results were to be expressed in terms of a unit of mass such as the proton mass, a unit of electric charge such as the magnitude of the electric charge of the electron, a unit of time, and a unit of distance. The effort to do that for atoms had been successful, so we were taught that atoms were understood. Questions were not raised about *why* the force that bound the atom was what it was, *why* the proton and electron had the same magnitude of electric charge, *why* the masses were what they were, etc. It is still that way today; in each subfield of physics some quantities are imported and not explained.

Particle physicists have achieved a Descriptive Understanding of our world, but not yet an Input and Mechanism Understanding because it is still necessary to input particle masses obtained through measurements in order to predict the results of experiments. It is hoped (see Chapters 9 and 11) that eventually the values of the masses can be calculated as a part of the theory. The physics underlying the Higgs mechanism (Chapter 8) also has to be understood before an Input and Mechanism Understanding of particle physics is achieved. Of course, different parts of an Input and Mechanism Understanding can be achieved at different times.

As the Standard Theory was developed it turned out that the mathematical form of each force could be derived from the rules once it was guessed that the force exists (see Chapter 4), and even the *existence* of a new kind of force is required if a new type of charge is discovered. This was more intellectually satisfying than having the forces be completely independent of the particle properties and the rules, and it stimulated a desire to derive more aspects of the theory that had previously seemed independent.

Unfortunately, there has been little progress in deriving the values of the masses.

There are twelve quark and lepton masses, and two new kinds of charge (color charge and weak charge, described in Chapter 4) in addition to electric charge. Although the masses can be measured, their values cannot yet be predicted by the theory. Once the masses are measured, everything depending on them can be calculated. There are even some additional quantities (Chapter 4) that have to be measured before all phenomena in the everyday world and all experiments at accelerators can be incorporated into what is describable by the Standard Theory. (A caveat is needed here about things that are too complicated to calculate in practice—we'll wait till Chapter 13 for that.) Today in particle physics this lack of knowledge of these nearly twenty quantities is considered intellectually unacceptable, and a great deal of research effort is put into trying to extend the theory so that all masses can be calculated as ratios to one basic mass. That goal is often expressed by saying that all mass ratios, such as the ratio of the mass of the electron to the mass of the muon, and the mass of the electron to the mass of the top quark, should be calculable. Similar goals hold for the other parameters, such as interaction strengths. Achieving those goals would take us beyond a Descriptive Understanding.

It takes at least three fundamental constants of nature to express everything else as ratios; they fix the units of measurement. They can be chosen in various ways, but the favored choices today are usually to use Newton's gravitational constant, **G**, Planck's quantum unit, **h**, and the speed of light (which we could call Einstein's constant), **c**. Although we will not use them much in this book, it is worth explaining them a little since they are very basic. Input and Mechanism Understanding essentially implies that all other measurable quantities can be expressed in terms of these three constants, or equivalent ones.

Newton's law of gravitation says that any two objects feel a mutual gravitational force that is proportional to the product of their masses divided by the square of the distance between them. In order to complete the specification it is necessary to say how strong the gravitational force is for two particular masses a specified distance apart, which requires multiplying the other factors by a constant (which we call **G**). That turns the proportionality into an equation. Similarly, one way to characterize the basic innovation of the quantum theory is to say that the energy levels of atoms are quantized rather than continuous. That is, they are only allowed to take certain values and not those in between. The spacing between levels is determined by Planck's constant, **h**.

Einstein's theory of special relativity follows from two assumptions. The first is that the formulations of the basic laws of nature should not depend on whether they are studied in a laboratory located here on earth, or in an airplane, or somewhere in outer space, or in any other frame moving at some speed relative to these. No one should argue with that. The second is more remarkable. It is that the speed of light (in free space) has the same value under all conditions. In particular, it does not depend on the speed of the source that emits the light. That is very different from our everyday experience. If we observe a person throwing a ball with some speed, and then observe her throw it again while passing by us in a car, we know that in the second case the speed of the ball relative to us is the combined speed the throw gave the ball plus the speed of the car; it is not the same speed in both cases. Light behaves differently (as do other things moving with nearly the speed of light). All light travels at a speed **c** (c is about 3×10^8 meters/second), whether it is emitted by a stationary flashlight or by one in motion.

MECHANISM UNDERSTANDING—BREAKING THE SYMMETRY OF THE EQUATIONS

There is a second aspect to Input and Mechanism Understanding for particle physics. Although we really want to formulate a set of equations that constitutes the underlying theory, what we see around us and in experiments is described by the solutions to the equations. The equations (hopefully) have considerable simplicity and symmetry, but the solutions usually do not. Often equations have many solutions; before it is possible to make predictions it is necessary to know which solution corresponds to our universe.

A simple (artificial) example may clarify this situation. Suppose the basic equation from the theory that predicts the masses of the electron, muon, and tau leptons is $E \times M \times T = 64$, where E stands for the mass of the electron, M for the mass of the muon, T for the mass of the tau, and the equation just says multiply the three masses and the product is 64 (in appropriate units). This equation has a number of solutions. For example, all the masses could be equal, $E = M = T = 4$. Or two could be equal and lighter, $E = M = 2$, $T = 16$. Or two could be equal and heavier, $E = 1$, $M = T = 8$. And which two are taken equal could be different, e.g. $E = 16$, $M = T = 2$. They could all be different, $E = 2$, $M = 4$, $T = 8$, or $E = 1$, $M = 4$, $T = 16$. In physics, of course, the equations are much harder to solve. One problem is to solve them at all, to find out if any solution looks like our universe. One might work hard for months to get a solution that turns out not to look like our universe—although maybe a different solution would. Even if it did look like our universe it would be necessary to show that it was indeed the right solution—why that one instead of a different one?

Note the important feature that the original equation for the masses is completely symmetric. It looks the same if you interchange the symbol for the electron mass with either of the other masses, or the symbols for the muon and tau masses, etc. The equation does not distinguish between the electron and the muon and the tau. But the solutions can give them very different masses. Today we suspect nature is like that—the Standard Theory equations are symmetric in many ways (some are described in Appendix B). The equations have a number of different solutions. The world is described by a solution that is not symmetric. If that could be derived, it would take us to an Input and Mechanism Understanding; some work in that direction is the subject of the next chapter, Higgs physics.

The jargon physicists use to denote describing the world by a nonsymmetric solution of a symmetric equation is "spontaneous symmetry breaking," and the state arrived at by doing so is called the "vacuum" selected by the spontaneous symmetry breaking. Input and Mechanism Understanding requires explaining why the vacuum state of our world is what it is in addition to knowing the equations of the theory. This is a new consideration in the history of physics. It occurs in the Standard Theory and in all attempts to extend the Standard Theory, and in other areas of physics, such as condensed matter physics.

Level III—Why Understanding

The third level of understanding—the "Why"—is the most ambitious. Having a Why Understanding would require being able to explain *why* things are the way they are, and *what* things really *are*. For example, claiming that a Why Understanding of particle physics was achieved would require a successful derivation of the existence of the electron, muon, and tau leptons, the values of their masses, and an explanation of why three (and only three) such particles that differ only in mass should exist. It would require explaining *what* electric charge is, *why* the forces are the ones we know and not others, and much more. While a Why Understanding is a fine goal, it may never be attained. As a proverb says, "The mere existence of a problem is no proof of the existence of a solution." However, achieving a Why Understanding of particle physics is a major research activity today (see Chapter 11), an attempt at a complete theory of "everything." The goal of achieving such a theory is ancient, but it has only become a practical research topic since the middle 1980s.

Historically, Why Understandings have been the domain of religions and mythologies. Believers often requested favors of the principals of their creation myths, although they never requested information as to the creators' construction techniques. They couldn't because they didn't have enough knowledge to understand the questions, let alone the answers. Having gained a Descriptive Understanding—a knowledge of how the world works—we are asking now for knowledge of the tools and the pattern. As we will see in Chapter 11, whatever the eventual outcome, the search for a Why Understanding is now legitimately in the domain of science.

Some people have argued that a full "theory of everything" can never be achieved by humans. And some people feel the human mind cannot comprehend the universe it is a part of—though no one has ever given a scientific argument for that belief. Some people think that throughout history every scientific

development opened up new questions and that process will continue indefinitely, so we will never reach final answers. Again, there is no convincing argument for that belief, and perhaps the analogy of the exploration of the surface of the earth is relevant—that geographic exploration continued for millennia, with every foray leading to further vistas, but it finally ended in the twentieth century. And some people are uneasy about religious implications of a theory of everything.

In practice, of course, the quest will go on. Since Galileo science has developed one step at a time. Those who consider understanding the universe important will push as far as they can. The glimpses so far of how nature works have shown an austere beauty, hinting at more. Perhaps a limit will be reached because of intellectual or technological or economic limitations, or because society considers the expense of experiments too great for the value given to doing science and understanding nature. Or perhaps eventually we will get there.