Chapter 1

Preliminaries

> *The opinion seems to have got abroad that in a few years all the great physical constants will have been approximately estimated, and that the only occupation which will then be left to men of science will be to carry on these measurements to another place of decimals.* — James Clerk Maxwell, 1871

This book starts with a description of our present understanding of how the universe works. Because this description relies on physics that we will not delve into until later, I must first present some basic results of special relativity and quantum mechanics (before we actually study them in detail in Chapters 5 and 7) so that the description makes sense. You will have to take my word that I am telling the truth; I can't *prove* these results until later, but they are necessary for understanding the basics of particle physics, nuclear physics, and atomic physics, all of which we will cover in the next few chapters.

In addition, it is helpful to have some idea of the historical sequence that physics went through, so I give a brief synopsis of the state of affairs at the beginning of the period we wish to study, and also at the end (in order to proceed, it is helpful to know where we are going).

1.1 Historical Preview

Physics circa 1900

In 1895 (before the discovery of X-rays,[1] radioactivity,[2] and the electron[3]) there were two *forces*: the gravitational force and electromagnetic force; there were two *object properties*: mass and charge; and there was one *dynamical law* determining how objects respond to those forces: Newton's law of motion. (Well, Newton actually enumerated three laws,

[1]Wilhelm Conrad Roentgen discovered X-rays on November 8, 1895, and was awarded the first Nobel Prize in Physics for 1901.

[2]Henri Becquerel discovered the natural radioactivity of uranium in early 1896 while investigating X-rays, and shared the Nobel Prize in Physics for 1903 with Pierre and Marie Curie.

[3]Joseph John Thomson discovered the electron in 1897 and was awarded the Nobel Prize in Physics for 1906. In reality, Thomson measured the charge-to-mass ratio of the electron in 1897, and it wasn't until 1899 that he was able to make an independent measurement of its charge (and hence its mass); the latter date, therefore, can be more definitively called the date of discovery.

but they act as one coherent group.) These, in principle, are all that you need to predict how objects will behave dynamically. The object properties determine the strength of the forces that act on the objects, and Newton's dynamical laws predict the future response to those forces. Thus, the universe was envisioned as a great clock—once started it would continue to run forever. In fact, if one were able to measure (with infinite precision, of course) the positions and velocities of all objects in the universe at a specific time (i.e., the "state" of the universe), then the laws of dynamics along with a knowledge of the forces would allow one to predict their future positions and velocities. This is known as the "mechanistic worldview" or the "Newtonian worldview."

In addition, the thermodynamic properties of matter and its interaction with light were relatively well understood. (Some of these properties are summarized in Appendix A.) So much so, in fact, that in 1875 the head of the physics department at the University of Munich advised Max Planck [Nobel Prize, Physics, 1918], the future progenitor of quantum theory, to not study physics because, as he put it, "Physics is a branch of knowledge that is just about complete. The important discoveries, all of them, have been made. It is hardly worth entering physics anymore."

However, there was little understanding of what matter was made. No theory satisfactorily explained why a particular object was endowed with its particular values of mass and charge. Many elements (such as nitrogen and oxygen) were known, and each element had a known molar mass and volume density, but no underlying reason for these properties had been successfully proposed. As you might guess, there had been hints about the microscopic structure of matter. For instance, the atomic hypothesis had been around since Democritus (c. 400 BCE), who postulated that rather than being a continuum, matter was made up of small discrete objects called "atoms". The word *atoms* comes from the Greek word $\alpha\tau o\mu o\sigma$, which means "that which cannot be cut," or "uncuttable." However, this hypothesis was nothing more than supposition until Dalton proposed his law of multiple proportions in 1803, which states that when two elements combine to form more than one compound, the ratios of the weights are ratios of small integers.

One of the clearest sets of data was the ratio of the amounts of oxygen and nitrogen needed to make various compounds.[4] Experiment showed that

$$\frac{m_O}{m_N} = 0.57,\ 1.13,\ 1.71,\ 2.29,\ 2.86 \tag{1.1}$$

for the five compounds nitrous oxide (N_2O), nitric oxide (NO), nitrous anhydride (N_2O_3), nitrogen dioxide (NO_2), and nitric anhydride (N_2O_5). The five ratios are very close to the integers 1:2:3:4:5. While this suggests that matter is made of discrete clumps, it would take another hundred years before the concept was accepted by the scientific community.[5]

[4] Friedman and Sartori, *The Classical Atom*, page 1

[5] For a detailed look at the history of the atomic concept, see Boorse and Motz, *The World of the Atom*, which contains reprints from Lucretius to Einstein concerning the existence of atoms and subatomic particles.

	smaller → (h)	
faster ↓	**Newton**	quantum
(c)	relativity	quantum field theory

Figure 1.1: A schematic diagram of dynamical theories. Newton's Laws are approximately valid when velocities are small compared with the speed of light, c, and another quantity, called "action," is large compared with Planck's constant, h. Otherwise, quantum mechanics or special relativity is needed, or perhaps both. When both are needed, the combination results in a "quantum field theory," such as Quantum Electrodynamics (QED) in the case of electromagnetism, and Quantum Chromodynamics (QCD) in the case of the strong/color force.

The discrete clumps turned out not to have exactly integer mass ratios, a fact that was first conclusively shown in 1920 by William Aston, who, along with Ernest Rutherford [Nobel Prize, Chemistry, 1908] developed an accurate mass spectrograph, and whose work included the discovery of isotopes in non-radioactive elements.

Physics circa 2000

The current view of the fundamental nature of matter and the ways in which it interacts is certainly more detailed than in 1895, and it is tempting to believe that we have reached "the end." However, while there are mathematical reasons that lead us to believe we might be near the "Theory of Everything," or a "Grand Unified Theory," past experience has at least humbled physicists of the present day and they understand that what we call "fundamental" today may turn out not to be. In fact, the situation today may be compared with that of 1895. We know of more (and smaller) particles, e.g., quarks, but, for example, we still have no idea *why* the quarks have fractional charge or *why* they have spin $\frac{1}{2}$, nor even *why* any of the particles have the masses they do.

We now know of four *forces*: the gravitational force and electromagnetic force, but also the strong nuclear force (or "color" force) and the weak nuclear force. We also can enumerate many more *properties* (or attributes) of subatomic particles: mass, charge, and color, which are related to the forces, as well as others that make sense only within the quantum description of matter, properties like spin and strangeness. Finally, we have expanded Newton's description of how these particles interact, with the result that his *dynamical laws* have been modified both on a small scale (quantum mechanics) and at large velocities (special relativity), as shown in Figure 1.1.

> The theory of *relativity* and the theory of *quanta* are the two great theoretical constructs of the early 20th century.

If you are interested in the intersection of quantum mechanics and relativity—quantum field theory—you will likely have to continue your work in graduate school because not only are advanced mathematical tools needed, but also a thorough grounding in nonrelativistic

Relativity	
special relativity general relativity	1905 Einstein 1915 Einstein
Old Quantum theory	
blackbody radiation photoelectric effect hydrogen atom	1900 Planck 1905 Einstein 1913 Bohr
Quantum Mechanics	
wave-particle duality wave equation matrix mechanics relativistic wave equation	1925 de Broglie 1926 Schrodinger 1926 Heisenberg, Born, Jordan 1928 Dirac

Figure 1.2: An overview of the architects of relativity and quanta, and when their key developments were produced.

quantum mechanics. Rather than diving headlong into these mathematically difficult (and conceptually abstract) topics, I will spend the rest of this chapter describing the basics in simplified terms. In this way we can attack the conceptual differences between classical physics and modern physics first, and then show later the mathematical detail of *why* they must be this way. Also, the mathematics and physics that we will need at first is nothing more than the basics of what you have learned in your study of introductory physics so far: energy, momentum, angular momentum, etc., and straightforward algebra.

Timeline

Relativity is, of course, the brainchild of one person, Albert Einstein [Nobel Prize, Physics, 1921], but quantum mechanics took many physicists many years to straighten out, as shown in Figure 1.2. How they were led to make the discoveries that they made was due to a long list of experiments that, for the most part, raised more questions than they answered. This list of experiments and predictions are given in Fig. 1.3. The first three experiments were essentially accidents, but the next two resulted from purposeful investigations into newly found, not understood phenomena. The next five, covering the first 15 years of the new century, were theoretical responses to the pile up of 19th century experiments that were inconsistent with 19th century physical theory. Key experiments were done during this time, however, they were continuing explorations of previous work rather than profound new advances. Most of these topics are covered in later chapters—those with an asterisk are analyzed separately in their own appendix.

Chapter 2

Introduction to Particle Physics

If I could remember the names of all the particles, I'd be a botanist.
— Enrico Fermi

Matter

At its most basic level, all matter consists of combinations of 12 elementary particles, which are listed in Fig. 2.1. They can be classified into two groups, leptons and quarks: quarks interact via the strong force but leptons do not. Both types of particles interact gravitationally (i.e., they all have mass) and via the weak force. Finally, all but the neutrinos interact electromagnetically because neutrinos are electrically neutral. The original motivation for the classification of leptons in 1947 was that the electron (the only known lepton at that time) was less massive than the proton and neutron (the only known nucleons—later determined to consist of quarks), and "lepton" is from a Greek word that means small or light. (See page 20.) Of course, after the discovery of the tau lepton in 1975 and the observation that it was almost twice as massive as a proton, the original reason no longer made sense. However, with the discovery of quarks and the fact that they are the only particles to interact via the strong force, the division into leptons and quarks is appropriate, albeit for reasons that have to do with forces rather than mass.[1]

Amazingly, all natural matter that we observe in the world around us consists of only three of these particles: electrons, up quarks, and down quarks. The atoms in our bodies are comprised of electrons as well as protons and neutrons, but the proton is made up of 2 up quarks and 1 down quark (commonly written 'uud'), while the neutron is 2 down quarks and 1 up quark (commonly written 'udd'). In this sense, the universe is very simple. There are only three particles, which combine in a myriad of ways to make up all the wonderful objects that we see: trees, rivers, oceans, mountains, planets, stars, and galaxies.

What are the intrinsic properties of these elementary particles? Two are very familiar, mass and electric charge, and three others, spin, magnetic moment, and color, are not as

[1] In addition to these 12 particles, there are the so-called "exchange particles," like the photon (denoted by the symbol γ), that mediate the four forces. These particles are also called "gauge bosons," or "intermediate vector bosons," and they are not normally considered to be matter. I will discuss them below on page 23.

e^-	**electron**	Leptons
ν_e	electron neutrino	
μ^-	muon (mu lepton)	
ν_μ	muon neutrino	
τ^-	tauon (tau lepton)	
ν_τ	tau neutrino	
u	**up quark**	Quarks
d	**down quark**	
c	charm quark	
s	strange quark	
t	top (truth) quark	
b	bottom (beauty) quark	

Figure 2.1: The twelve elementary particles that comprise all natural and man-made matter. The three particles in boldface — electron, up quark, and down quark — comprise all known natural matter. There are six leptons (three massive leptons and three massless neutrinos) and six *flavors* of quarks.

familiar. We will examine these five in detail in Sections 2.1 through 2.5. Of course, there are many others, such as strangeness, isotopic spin, lepton number, and baryon number, and we will investigate these in later chapters. The nomenclature of particle physics is very complicated, but if you remember to characterize particles based on their fundamental properties, like mass, charge, etc., it doesn't matter what they are called, you will be able to understand the physics of their interactions.

You may have noticed that I didn't mention size as an intrinsic property. The reason is that all of these elementary particles are thought to be point-like and have no size. For example, the size of an electron has been experimentally measured to be less than 10^{-22} meters![2] This simply means that the electric force that an electron feels is Coulombic (i.e., $\sim 1/r^2$) down to that distance, which means that there is no reason to think that electrons have any structure at any scale. Of course, when elementary particles combine to form protons, neutrons, atoms, and molecules, the physics of their interaction occurs on a spatial scale so that the conglomerations acquire a characteristic size and shape.

There is another characteristic of these particles that has no classical counterpart: they are identical and indistinguishable. Unlike our macroscopic world, where we can paint seemingly identical objects different colors to distinguish them (billiard balls, for example), in the microscopic world there is no way to tell two electrons apart. When a cue ball, say, collides with an eight-ball and they each move off in different directions, it is clear which ball is which after the collision. However, if two electrons collide and move off, the experimenter is not able to distinguish which electron is which after the collision. As we will see below, this fact has far-reaching implications on the allowable motions of these particles. The most well-known implication is the Pauli exclusion principle that is applied to electrons within atomic orbitals, which I will discuss in Chapter 4.

[2] Hans Dehmelt, "A Single Atomic Particle Forever Floating at Rest in Free Space: New Value for Electron Radius," *Phys. Scr.* **T22** 102-110 (1988)

e^+	positron (anti electron)	anti Leptons
$\overline{\nu}_e$	anti electron neutrino	
μ^+	anti muon (mu lepton)	
$\overline{\nu}_\mu$	anti muon neutrino	
τ^+	anti tauon (tau lepton)	
$\overline{\nu}_\tau$	anti tau neutrino	
$\overline{\mathrm{u}}$	anti up quark	anti Quarks
$\overline{\mathrm{d}}$	anti down quark	
$\overline{\mathrm{c}}$	anti charm quark	
$\overline{\mathrm{s}}$	anti strange quark	
$\overline{\mathrm{t}}$	anti top (truth) quark	
$\overline{\mathrm{b}}$	anti bottom (beauty) quark	

Figure 2.2: The twelve elementary antiparticles.

Antimatter

Antimatter is as much matter as matter is matter. — Abraham Pais[3]

For every particle, there is a corresponding "antiparticle," with the same mass, but opposite electric charge, and these are listed in Fig. 2.2. The antiparticles are denoted by an overbar, or sometimes by simply changing the sign, as with the positron. Do not ascribe any mysterious properties to antimatter. As Pais implies, from an antiparticle's point of view, *we* are made of "antimatter." In fact, current cosmological theories suggest that in the early universe, a short time after the Big Bang, there was approximately as much matter as antimatter. As the universe cooled, equal amounts of matter and antimatter were annihilated, and what was left over was the small amount of matter that makes up the visible universe. The question of why there was an asymmetry between the amounts of matter and antimatter (i.e., why there wasn't exactly the same amount of both kinds) is one that still has not been answered.

Why, then, does antimatter exist? No one knows, but that appears to be the way the universe is made. However, within the rules of our current structure of theoretical physics, antiparticles are a "necessary consequence of combining special relativity with quantum mechanics."[4] Paul Dirac [Nobel Prize, Physics, 1933] was the first to realize this fact when he attempted to construct a relativistic wave equation for the electron in 1928 (the Schrodinger equation was not relativistic). The mathematics implied the existence of positive electrons, which later turned out to be positrons.

[3] Abraham Pais is perhaps one of the foremost chroniclers of the story of modern physics. His writings, listed in the Bibliography, are all the more valuable because he was a practitioner — he worked on the front lines in 1940s through the 1970s — and he knew and collaborated with several of the key players personally, e.g., Bohr, Einstein, Heisenberg.

[4] Martin and Shaw, *Particle Physics*, p. 2.