Chapter 1: Introduction to the Physical World

The realm explicable by science is not the entire universe of human experience. Science attempts to organize, or make sense of, human experience with reality. Scientists have developed a world-view that stresses questioning of all things. Experiments are ways of asking questions of Nature. Methods of doing science focus on the production of ideas that can be tested and determined to be useful or false by experiments, which are reproducible. The experimentation over the last three hundred years has led to the establishment of a body of useful knowledge. The scientific approximation to reality is being continually refined. Some facets of the successes of science are illuminated by an examination of the investigation of the structure of matter. A study of the structure and behavior of matter (made up of little points of smaller constituents) can serve as a guide to the subject of physics. This theme is carried throughout this book.

1.1 What is science, exactly?

All people alive experience the world—Nature—in some way. They try to explain it to themselves somehow. People make mental pictures of the way the world behaves to make sense out of the world. These pictures or explanations are limited by people's prejudices, as well as by the limitations in ability to experience facets of the world because they are human beings. We can never overcome the fact that we are born human; we simply have to live with explanations that reflect human limitations in imagination and perception. This limitation is true whether the explanation of the behavior of the world smacks of science or of superstition. Of course, groups of people working together can eliminate some individual limitations, but not limitations stemming from people's innate humanness.

Some people attribute the apparently inexplicable to gods or demons. Others think in terms of chance happenings. Still others choose the language of science. These are various valid ways of describing one's experience. In this book, we concentrate on the great vision that science gives to humanity, a vision that allows humans to transcend some of the limitations thrust upon us by our birth, a vision that finds beauty and harmony in the workings of Nature.

Scientists choose one particular way of describing and viewing the world. Science creates words to describe aspects of reality. These descriptions are organized in terms of laws that govern the workings of the universe. All laws or theories are *models* of reality, the way the world works. The physical laws are describable in terms of the language of mathematics. Human beings can only create approximations to reality through their mathematical models. This physical world view is very circumscribed—scientists do not pretend to explain everything. However, scientists do pride themselves on their view because it gives them real power to describe the world *as it is* and the power to make predictions about the way the world behaves.

It is a very difficult challenge to become a scientist because scientists are people who have to give up many of their prejudices about how the world works, and learn how the world actually works in the sense they are describing it. It is hard to give up timeworn ideas, sometimes especially so when they are wrong. Nevertheless, scientists attempt to do this as best they can. The goal of science is the accurate description of Nature [which implies at least limited understanding]. Nevertheless, as people become more sophisticated, their ideas become more sophisticated, and their models of reality become more subtle.

Part of the training of all new scientists involves their learning how to trust what knowledge has been gained up to the present. They often repeat for themselves key experiments that convinced previous generations of scientists of the utility of a particular description of some natural phenomenon. They gain much more experience of how the world seems to work than ordinary people because of their questioning and their experimental approach. As part of this process, they examine the limitations in the accepted scientific description of Nature.

Scientists agree to give up their prejudices and profess to accept the dictates of experiments they or others perform. Since science is a human endeavor, scientists do not always attain their ideals. However, they try to live up to them as well as they can. For doing so, they learn to ask questions of Nature and to find out some of the ways that the natural laws work. A very important part of the process of thinking as a scientist is the questioning of everything. To most scientists, the questions are more important than the answers. The learning of how to ask the right questions is the most difficult hurdle to becoming a scientist.

Example 1.1

Prior to the Renaissance, Earth was thought to be the center of the universe. This idea does not affect a person's everyday life or behavior. Why did everyone's viewpoint eventually change?

Those persons involved in the rediscovery and generation of new knowledge about the universe rejected this old viewpoint as the result of both experimental and philosophical effort. The "average" people couldn't have cared less about Earth's position in the universe, but the weight of evidence that convinced the educated people eventually won more and more converts as the mass of people emerged from ignorance and more and more people chose science and engineering careers. Nowadays virtually everyone rejects an Earth-centered universe. The heliocentric model of the solar system evolved into a model of the solar system as an insignificant mote on an outer spiral arm of the galaxy; then we learned that our Milky Way galaxy was just one among many indistinguishable galaxies.

Instead of causing depression, this progress evokes admiration for the grandeur of the universe, and allows people to appreciate the wonder of starry nights more than ever.

When we were small children, we often asked our parents "why" questions such as "Why do I fall when I jump from the porch rail?" No scientist can answer that question despite the progress in understanding Nature over the last 400 years. Scientists can never answer "why" questions; it is beyond our frail powers as human beings. Scientists, physicists in particular, can ask and answer *some* simple "how" questions. For example, we may describe *how* you fell when you jumped off the porch rail. "Why" questions ask for what I may call theological answers. If you ask another person why that person did a particular thing, you are searching for an explanation of that person's state of mind. If you ask why something is a certain way about the world, you are asking about the state of mind of some higher power [you might say God]. The answers to "how" questions are restricted to descriptions of the way things work. This physics can do splendidly, without needing to address the "why" question at all. This is the reason that scientists run the gamut in terms of their religion from the devout religious person through the agnostic to the atheist.

Example 1.2

The famous physics professor, Prof. Fizz Icks, jumps from his porch to the ground. What is the difference between *how* he falls and *why* he falls?

All bulky objects near the surface of the Earth fall toward Earth's surface because Earth attracts all objects in its vicinity. This answers how. This answer does not explain why because it has not explained the reason that there is an attraction that exists in the first place. Physics can push back the border between how and why by developing a theory of gravity, but this still does not ever explain the ultimate answer to the why.

Another common view of science from the outside is that it is a collection of facts. Nothing could be further from the truth. Science [and especially physics] does deal in facts, all right. These facts are only the excuse for asking specific questions. What I mean by that may seem obtuse to you. Let me use an example to try to clarify what I mean. You can experience music. The music can be described by a series of notes; many sequences of notes lead to what I would call music. The notes are similar to the facts; the music is the analog to science. Most readers would agree that music is *not* just a collection of notes; similarly, science is more than a collection of facts. Another example is the construction of sentences from words, just as scientific theories are constructed from facts. The eminent French scientist Henri Poincaré said

> Science is constructed of facts, as a house is of stones. But a collection of facts is no more a science than a heap of stones is a house.

Science explains facts. It connects facts. It includes facts. But it is more than the facts themselves. Science is the human way of understanding how the world works as far as human beings can understand it. It is a way of making connections among seemingly disparate facts or ideas. It is a way of simplifying descriptions of Nature. The idea that there is simplicity to be found in Nature is called reductionism. Scientists and engineers are reductionist by inclination.

The use of the word "theory" in science causes confusion. To give an analogy, suppose that a corpse is found with an arrow protruding from it. Detective A investigates the murder. He says, "I have a theory that tiny little cupids winked into existence and shot the arrow into the body with their little bows." This is a "theory" in name only. It has no real connection to what a scientist would mean by a theory, because there is no evidence for this to have happened. There is no indication that it could ever happen again this way.

A scientific theory would be based on evidence. Detective B also investigates the murder. Detective B might say "My theory is that some person shot the arrow into the victim, and that I should be able to find that someone. I checked the arrow for fingerprints. I found some, which I'll match with my files. I also found that it was manufactured by the Straight Arrow Company, batch # C11-23. Straight Arrow is a local company, so I can find out where they sent an arrow with this batch number. Then I will ask at that store who might have bought an arrow from this particular batch. With a photo of the person whose fingerprints I have, I can see if this person bought those arrows." Which detective would you want to bet would catch the perpetrator?

Central to the scientific world view is the notion of *falsifiability*. We say in any cases in which a theory's predictions could possibly be shown by experiment to be false that the scientific framework [or theory] describing Nature is *falsifiable*. This means that the theory provides predictions that can be tested against Nature, and judged false if they are not correct descriptions.

Physics makes predictions based on theories or laws of the way Nature works. Physics is by its nature falsifiable. Much of what people label as "theories" in casual speech is not falsifiable because the "theories" are not subject to experimental checks, and thus not theories at all. The first detective's "cupid theory" of the murder is not falsifiable, but the second detective's "arrow theory" is. The difference is that the "arrow theory" can be checked and shown to be true or false. It is not possible to check and verify the "cupid theory."

Scientific descriptions should predict the behavior of nature. Scientists make theories that attempt to explain how Nature behaves. If physical descriptions are correct, predictions arise from physical theories that describe what *should be* observed if a new experiment were to be performed. If what *is* observed after the experiment is actually performed is different from what was predicted by the theory, then either there was an error in performing the experiment or the framework that led to that prediction is false. Most experiments are run independently by several scientists or groups of scientists at different times in order to insure as far as possible that the experiment was performed correctly.

Scientists analyze their data by comparing them to previous results, and to their expectations based on models constructed from theories. It may be clear that the hypothesis is correct. Then the work is done. If the hypothesis is rejected, it may be necessary to formulate new hypotheses and test them. Sometimes it is not possible to decide whether the hypothesis is accepted or rejected. In this case, it may be necessary to repeat the experiment with more sensitive instruments, or it may be impossible to make accurate enough observations with current scientific instruments.

Example 1.3

Tycho Brahe (1546-1601) worked every clear night for many years to record the positions of the planets in the sky. Johannes Kepler (1571-1630) was able to infer from these data that the planets of our solar system revolve in elliptical orbits about the sun. Isaac Newton (1642-1727) showed that Kepler's elliptical planetary orbits resulted from gravitation, the same thing that causes objects near Earth to fall. Explain how this chain of connections illuminates the process of science here.

Newton explained the results that Kepler inferred from the facts of Brahe. Brahe provided the basis for synthesis by Kepler, an observation that the planets behave similarly. The observation is explained as a small part of the construction of a theory of gravitation by Newton.

The natural course and purpose of science is for experiments to be performed to collect facts, and then for a model to be generated to provide a consistent framework that encompasses the explanation for these facts among others.

Often, the results of experiments raise more questions. This is what keeps science interesting. Scientists are excited by the prospect that they might be able to prove that some theory leads to predictions that are not in agreement with experiment. Those able to show such experimental disagreements with theory are respected by others for their cleverness and perseverance. Experimental evidence that a theory's predictions are faulty is important. Scientists who are limited by technical ability to check whether a theory is false often design new technology in order to be able to surpass their limitations.

Example 1.4

In the phlogiston theory, heat was believed to be a fluid transferred from place to place. Indeed, heat does appear to have the behavior of a fluid as it "flows" through an object, or between objects. One prediction of the phlogiston theory was that, for objects of the same size and substance, a warmer object should weigh more than a cooler one because the "phlogiston" fluid itself should have weight. This prediction ultimately proved false. Does the fact that the phlogiston theory was a scientific theory and was incorrect and incomplete mean science and its processes were wrong in this case?

The phlogiston theory is an example of a theory that could explain some aspects of heat, flow, but could not explain its underlying nature. The later kinetic theory could explain heat flow and account for its nature in terms of random motion of molecules. The kinetic theory models heat flow through the microscopic structure of matter.

The phlogiston theory did not really explain heat flow, but the model allowed scientific questions to be asked that eventually showed that the model was wrong in its predictions. It was useful to the scientists studying these phenomena because it allowed them to construct appropriate questions. Incomplete models and wrong explanations are necessary way-stops on the road to better understanding in science.

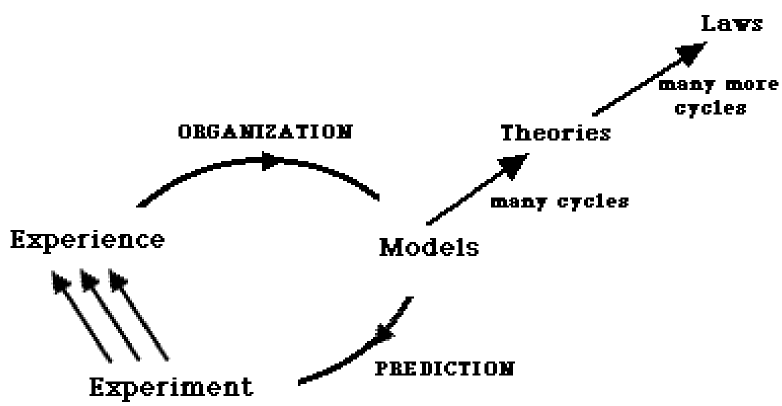

Fig. 1.1 A schematic view of the process of science. Theories are the result of gathering confidence in models. Laws are theories that have been tested by time.

In Fig. 1.1, we present a picture of the process of model-building that results in a description Nature in which physicists (and scientists in general) are confident. The discovery of the regularities, or laws, of Nature result from many attempts to prove them incorrect. By default, by their *not* being proven wrong in so many attempts to do just that, these descriptions can be taken to be accurate reflections of the world around us.

The repeated testing, again and again, of these behaviors of Nature gives rise to confidence in a description that cannot be proved wrong by the most prodigious efforts of scientists to do so. We can in good conscience act as if the laws describe proven relationships. We can be confident that the model describes repeatable reality as tested by experiment very well. Many of the "laws of physics" are of this sort, and physicists are confident in them. Many physical understandings of Nature are more provisional models, which may some day after more testing merit the designation of law. Some models may be dropped or replaced by more accurate ones. Experiment is the final arbiter of any model. Scientists agree to abide by Nature's dicta.

1.2 Science and Technology

Engineering and science are married. In general, science can be defined as the attempt to explain Nature. Engineering is the art of making utilitarian application of the fruits of scientific research, that is, of creating technology. Technology is the application of scientific discoveries to the design and construction of practical apparatus. To return to the musical analogy used above, the scientist is like a composer and the engineer is like a musician.

Scientists conceived of and investigated radio waves. Engineers designed and built radios and televisions. Scientists discovered x rays. Engineers designed x-ray tubes. Scientists discovered radioactivity. Engineers built machines that use radioactivity to help cure cancer. Scientists developed a theory of microwave radiation; engineers developed (microwave) radar and microwave ovens.

Without engineers, scientists would not have their apparatus to ask questions of Nature. Without scientists, engineers would have to become scientists themselves. Indeed, engineers sometimes act as scientists and scientists sometimes act as engineers.

Both engineers and scientists are concerned about dealing with the reality of the world as far as they can perceive it. In this book, you will be introduced to the study of reality as far as human beings can understand. In particular, you will learn about the models physicists have developed to describe Nature. You will also see a little about how physicists develop models of the natural world.

Example 1.5

James Clerk Maxwell (1831-1879) put the theory of electricity and magnetism into a coherent whole. From this theory, he predicted the existence of electromagnetic waves.

Light, radio waves, and microwaves are some examples of these waves. What does this success say about the processes of science? What developments led from his theory to engineering practice?

This is an example of a theory that summarized and organized previous knowledge of a phenomenon and successfully predicted the existence of new phenomena. Also, Maxwell’s theory tied together two phenomena that no one had expected to be related before. The successes are no more important than the failures in the broad perspective on science.

The development of radio and television, among others, can be traced directly to Maxwell’s insights.

1.3 The ancient view of the world

Human beings from time immemorial have tried to understand and simplify their world. Science is descriptive of the world. Classification[§] plays an important role in science. The use of classification is not the classification itself, but the possibility that the classification can lead people to a simplification by the fitting together of what originally seem to be different elements, or by the discovery of an overarching pattern. The modern atomic view of matter arises from such classification and such impulses. The contemporary approach is to describe as well as possible, to classify, and then to use experimentation based on falsifiable theories to extend and embellish that description.

Aristotle and other Greek philosophers tried to describe their world as they experienced it. They observed that the world was seemingly made from myriads of objects. There is so much variety in the world! Rocks, water, plants, animals, and so on. They, too, tried to simplify. They believed that the world was made up of only four basic parts—earth, air, fire, and water. The Greeks actually acted as scientists in this classification scheme. They looked at the things of the world, observed similarities among the various things, and then recognized that there were “basic” elements. Today, we recognize even more variety than the ancients could have. Over ten million different chemical compounds have been cataloged. You, too, as a child observed the world to be filled with an incredible variety of objects.

[§] Simple classification consists of describing by assigning a word to a quality or thing. More complex classification involves recognition of similarities among the qualities or things, establishing categories, and then recognizing similarities among categories, establishing families, and then recognizing similarities among families, and so on. Finally, the most complex classification is explanation of the reason for the groupings. This is one role of theory in science.

The Greeks prized unity, but disdained experimentation because they believed that all knowledge could be derived by "pure thought." In the language of modern physics, they were theorists. The Greek philosophers attempted to explain their world by pure thought, without trying to design experiments to test their results. The Greeks were expert geometers. Their geometry was based on simple "self-evident" ideas, such as that parallel lines can never meet. Their success with geometry had persuaded them that all knowledge could be derived from self-evident ideas. This is a case in which success can sometimes lead to wrong conclusions. In the nineteenth century, mathematicians showed that the "parallel lines" proposition was neither self-evident nor always true. Two lines that are perpendicular to the equator are parallel, but if the lines are followed along Earth's surface, they will cross one another at the poles.

The Greeks never considered the notion of falsifiability or its usefulness in sorting out good ideas from useless ones. Unlike the ancient Greeks, contemporary theorists pay great attention to experiment. They try to fit the physical ideas into the real-world framework set by experimentation. The era of falsifiable experimentation has now lasted over three centuries, and helped to discover many useful ideas that codify how the world works.

How could the Greeks unify this multitude of objects they observed? They described their world as made of smaller elements as mentioned above: Earth, air, fire, and water were constituents of all objects. It seems unlikely that the millions of different substances that are observed can all be made out of a few "elements." The Greeks had no tools for synthesis. Since they had no experimentation—only mentation—they had no way besides esthetics to decide on which theory was "correct." By "correct" here, we mean that it could be used for predictive purposes. Such a caveat would never have been recognized by the Greeks. It demonstrates a thoroughly modern world outlook to think of *experiment* and *prediction* as important goals of a picture of Nature.

The Greek philosophers Democritus (c. 464-c. 370 BC) and Leucippus (5th c. BC, active 450-420 BC) introduced the atomistic view that, modified, we accept today. While they were able to propound their ideas, the ideas were not accepted. No Greek philosopher would think of performing an experiment of any sort. They would probably have argued that they have seen rock crushed; the crushed rock can be ground to powder; the powder could be pulverized; and had their listeners imagine the same process continuing until the smallest unit, the atom, was produced. In any case, they would not have been able to perform any experiment that could have tested their ideas. All their discussion was of a theoretical nature, as was the uniform rejection of their notion by their fellows. The idea of falsifiability, and the concomitant requirement of experimentation, had to develop before the further understanding of the structure of matter could continue.

Different Greek philosophers described and discussed motion, a very important part of the world we observe. They developed a sophisticated phenomenology of motion—a "common-sense" description of the way that objects move, and one that worked reasonably well for them and the many generations that followed them. For example, the Greeks reasoned that objects fell because "like seeks like." Earth-type objects (solids) seek the Earth [that is, fall to the ground]. Water-type objects (streams) seek like (rivers), which seek like (the ocean).

Many authorities believed that any object set into motion would naturally stop. That probably *sounds* reasonable to you and to them, although as we shall see below, it is not a useful view of the world. In fact, the reason that the objects stop is that there is an agent we call friction acting on them. Real-world objects that are not forced to stop, as by friction, would continue to move without change in their motion. Of course, the Greeks had little experience with ice or other semi-frictionless surfaces. They had no ideas about the microscopic nature of the world that they could accept, so they had no ideas about how friction, for example, could work. The more modern idea of continuing motion of objects once set into motion would have been rejected as silly by pre-Renaissance authorities who believed that the Greeks were correct in all things, yet it contains the larger, if seemingly unlikely, truth.

Example 1.6
What is a reasonable modern scientific-technological attitude toward authority?
Respect for the vouchers of authority can sometimes prevent a person from seeking the truth. Scientists and engineers tend to trust more in experimental results, that is, they tend to be

skeptical of the authority of a person's utterances. The "truth" is seen as the result of experimentation.
An old piece of advice given to people is that if respected scientists or engineers claim that something is possible, they're probably correct. If these same authorities claim that something is impossible, they will often be wrong.

1.4 The modern world view

A better description of Nature was discovered, over 300 years ago, by experimentation. The novel ideas of the Renaissance, especially traceable to Sir Francis Bacon's (1561-1626) codification of what we would now call scientific method [which included the idea of falsifiability], overthrew the teaching of written authority. The new birth of thought encouraged the rise of questioning, and of ways to *test* the answers to the questions that science uses today.

Think again of ten million compounds. To the human mind, this presents an incomparable richness, an almost infinite variety. Today it is known that all this variety, these millions of molecules, comes from combinations of only about one hundred elements. The simplification that results from being able to describe the world in terms of a hundred building blocks instead of millions of compounds is obvious. How can we know that this variety is made of compounds, or, alternatively, how do we know that there are elements?

The British scientist John Dalton (1766-1844) proposed two laws based on his experiments—the law of definite proportions and the law of multiple proportions. He had observed that the masses of reactants in chemical reactions combined in definite proportions, for example, water was not an element, but rather consisted of two volumes of hydrogen for every one of oxygen with masses in the ratio of 1 to 8. Some "elements" can combine in more than one way, but the masses were in the ratios of whole numbers.[†] He approached his explanation from the reductionist framework.[¶] That means that he assumed that the combination results could be explained if chemicals were composed of two or more constituents. This hypothesis is subject to falsifiability, but was never proved false.

Example 1.7
Originally, falsifiability was developed as part of questioning the claims of authority. How has the questioning evolved since that time?
The questioning attitude of science has expanded from the challenging of unsubstantiated avowals to the search for new structures and interrelations among facets of knowledge. Some scientists check and recheck the experimental claims of others to test results and interpretations, and to uncover possible experimental error. Other scientists seek new experimental discoveries. The claims of a new theory are tested if the existing technology allows it.

The point here is not the details of the working through of the hypothesis, but rather the fact the scientific advance comes from stretching the boundaries of the possible. The consequence of Dalton's idea is that the whole is composed of smaller units. This was a tremendous advance—a true synthesis. All matter was made out of building blocks called molecules (or sometimes atoms). The molecules were in turn made up of atomic building blocks. The new knowledge also allowed chemists to introduce a rational naming scheme for compounds, one still being extended today.

[†] This is the law of multiple proportions. For example, nitrogen and oxygen combine to form both nitric oxide (NO) and nitrogen dioxide (NO_2). Thus, one volume of nitrogen could combine with one volume of oxygen in a ratio of masses of 7 to 8; or one volume of nitrogen would combine with two volumes of oxygen with a ratio of masses 7 to 16.
[¶] It should be pointed out that, although the reductionist approach is to find the pattern or the simplicity in Nature, it is not true that this is a *simplistic* idea. The reductionist view is very subtle as well as simplifying, but it does not replace reality by oversimplification or concentration on only one aspect of the reality described.

1 → Atomic number
H → H—Symbol
1.00794 → atomic mass

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1 H 1.0079																4.0026	2 He
3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.54	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79 90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc 98.91	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	57 La to Lu 71	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po 209	85 At 210	86 Rn 222
87 Fr 223	88 Ra 226.0	89 Ac to Lr 103	104 Rf 261.1	105 Db 262.1	106 Sg 263.1	107 Bh 264.1	108 Hs 265.1	109 Mt 268	110 269	111 272	112 277		114 289		116 289		118 293

Lanthanide Series

57 La 138.9	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm 144.9	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0

Actinide Series

89 Ac 227.0	90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np 237.0	94 Pu 244.1	95 Am 243.1	96 Cm 247.1	97 Bk 247.1	98 Cf 251.1	99 Es 252.1	100 Fm 257.1	101 Md 258.1	102 No 259.1	103 Lr 262.1

Fig. 1.2 The Periodic Table of Elements

Amadeo Avogadro (1776-1856) was the first to propose that equal volumes of a gas at fixed pressure and temperature contained equal numbers of constituents. After a long time, the number of constituents in a specific amount, called a mole,[§] was determined.

Dmitri Mendeleev (1834-1907) and other chemists spent time looking at the properties of chemicals that were identified as elements (in the modern sense). Mendeleev is recognized as the creator of the first periodic table of the elements. In the periodic table, the atoms are roughly ordered by their atomic masses, which appear to be almost in ratios of whole numbers. The columns of elements (the periods) have similar properties. Regularities in atoms are seen in similar tendencies of all atoms in a given period to combine with another specific atom. With such an organization, regularities in similar melting points, similar ionization energies, and so on become more apparent. The atoms seem to fit in “families” that have similar properties. Some places on the original periodic table seemed to demand to be empty, as no species of element having the expected properties was seen. This hypothesis is falsifiable, but could not be proved wrong. Mendeleev predicted that elements having these properties would soon be discovered, and the experimental discovery of “eka-silicon” [now called germanium] sealed the acceptance of the periodic table. This property of a periodic structure hints at the existence of sublevels in the atoms. See Fig. 1.2.

The periodic structure of the organization caused chemists and physicists to ask new questions about the structure of the elements. There now came a period of experimentation in attempting to penetrate to the sublevel that these regularities in the experiments hinted at. In the 1890s, so-called cathode rays were identified as electrons by J. J. Thomson (1856-1940) from the way they bent near magnets. Around 1900, the proton was discovered and the mass was measured by tracking beams of positive particles, also by Thomson. These discoveries led to the development of new hypotheses, new experiments, asking even more subtle questions. Questions lead to new discoveries, which in turn lead to new questions, *ad infinitum*.

At about this time, radioactivity was discovered. Some atoms expelled certain “rays” from them, rays which were differently charged or not charged at all. These rays could be detected indirectly from their ability to expose photographic paper or cause a phosphorescent screen to scintillate. New Zealander Ernest Rutherford (1871-1937) (with chemist Frederick Soddy (1877-1956)) was able to explain the law of radioactive decay.[¶] Rutherford moved to England from Canada and founded a laboratory at Manchester, and

§ A mole is the amount of a substance having a mass in grams equal numerically to the atomic mass.
¶ In the paper (E. Rutherford and F. Soddy, *Phil. Mag.* **5**, 576 (1903)), Rutherford and Soddy introduced the decay constant for radioactive decay, λ, which is related to the decay time by decay time = $1/\lambda$, and found that it is the

his laboratory became a mecca for scientists from all over the world. Scientists at the laboratory performed numerous experiments on atomic nuclei and did experiments scattering helium nuclei from gold foil that conclusively demonstrated that atoms are mostly empty space, with the protons gathered in the center. The Geiger-Müller counter, a detector of radioactivity, was first developed in Rutherford's laboratory.

Henry Gwen Jeffreys Moseley (1887-1915), in Rutherford's lab, used scattering of x rays from the nuclei of atoms to test the distribution of charges in the nucleus. He found that the number of protons in the atom, Z, determined the frequency of x-ray spectral lines. This allowed Moseley to determine the number of protons in the nuclei of all elements easily, as we shall see in Ch. 32.† The number of electrons is equal to the number of protons in the nucleus attached to the atom. The nucleus was found through experiment to have a size of about 10^{-15} m, and the atom a diameter of roughly 10^{-10} m. Thus, the atom is 100 000 times larger in diameter than the nucleus. If we liken the nucleus to a pea sitting at the center of a football field, the atom's outer electrons are about as far away as the outermost seats in the upper reaches of the stadium.

The original periodic table was organized roughly by atomic mass, but Moseley's findings showed that this ordering was sometimes incorrect (for example, cobalt and nickel were in the wrong order [Fig. 1.2]). Moseley's work was initially controversial because he would change the sequence of the atoms in the periodic table slightly. He found that this change improved the periodic table, in that it made the sequence of melting points, etc., more in line with the observations. Moseley was also able to identify missing elements from gaps in his data. This left a puzzling question, though: Why was the order of the atoms not in terms of the order of the atomic masses?

Finally, in 1932, the neutron was discovered by James Chadwick (1891-1974). Chadwick looked at examples of penetrating radiation, and realized that the radiation was actually a particle that was electrically neutral. The neutron was very much like the proton except that it had zero charge and its mass was slightly greater than the mass of the proton. Moseley's missing information was the fact that a number of neutrons also sit in the nucleus. Each nucleus has Z protons and N neutrons, so its atomic mass is about $(Z + N)$ m, where m represents the proton's mass. This explains why the atomic masses are roughly in the ratio of integers. This led to new synthesis. The atom is made up of a nucleus that contains protons and neutrons and the atom itself has a size determined by the outermost electrons orbiting the nucleus.

The neutron was the last building block needed to explain the structure of atoms. Atoms and their observed regularities could now be explained in terms of the three constituents: proton, neutron, and electron. This synthesis, which explains the one hundred or so atoms in terms of just three constituents was similar to the achievement of the chemists in reducing the millions of chemicals in the world to molecules made up of just a hundred atoms.

The substructure of molecules is atoms. The substructure of atoms is protons, neutrons, and electrons. The discovery of the chemical structure led to the discovery of the atomic substructure. The examination of the atomic substructure led to the discovery of the nuclear substructure. Would examination of the nuclear structure lead to a new substructure?

Example 1.8

Is physics just the study of the structure of matter?

No. While this structure is important, it is not everything. For example, the way a particle of matter moves can be considered independently of its structure. The overall behavior of matter is the interest of physics, and this study has led to the great expansion of knowledge and understanding. The study of the way that particles interact with each other has led to other discoveries such as the various conservation laws and the concept of the field.

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proportionality constant between the rate at which radioactive materials decay and the original number of radioactive atoms.

† Moseley said "We have here a proof that there is in the atom a fundamental quantity, which increases in regular steps as we pass from one element to the next. This quantity can only be the charge on the central positive nucleus."

1.5 Dashed hopes of simplification: Discovery of new Particles

At around this same time, 1932, a new kind of particle representing a new kind of matter was found in experiments. Carl Anderson (1905-1990) found an example of a track left by a charged particle in cloud chamber photographs that looked as if it must have been left by an electron, but that curved in the wrong direction to be an electron [Fig. 1.3].

Fig. 1.3 Anderson's positron observed in a cloud chamber. An electron would have curved to the right due to the Lorentz (or electromagnetic) force applied. The observed track is consistent with an electron in causing bubbles, but curves to the left.

It thus had the "wrong" charge to be an electron, positive rather than negative. Anderson had discovered what we now call antimatter—the positron, which is now known to be an antielectron. If an electron meets a positron, the particles will combine to produce a burst of energy. A particle and its antiparticle annihilate one another.

We have subsequently found that for every type of particulate matter in our universe, there exists an antiparticle. What is antimatter? How do we describe antimatter? This raises an even bigger question: How could the universe as we know it be made of matter, not antimatter? Why are there not equal numbers of atoms and antiatoms? Many attempts to answer this question have been made, but there is as yet no truly satisfactory answer.

The antielectron was the first of many particles that were not the simple proton, neutron, or electron to be discovered. The simplicity so carefully constructed had collapsed. A reductionist would suspect that this was an indication that there was another sublevel that would be simpler and would explain the pattern of these "new" particles observed in experiments.

A particle called the muon was discovered in the 1930s. The muon is similar to the electron, but with a greater mass (about 200 times the electron mass). The muon really behaves just like a heavy electron. The Nobel-prize winning physicist I. I. Rabi supposedly said, upon hearing of the muon's discovery, "Who ordered that?"

Example 1.9
Why might Rabi have said this?
The appeal of the simplicity of the electron-proton-neutron picture of matter was so strong that he had to wonder about the reason there was a muon. The question of how the muon fits into the overall scheme of things is not as yet totally answered.

Now physicists were faced with a world containing protons, neutrons, electrons, and muons. Furthermore, the neutron was found to decay into a proton and electron, and a study of its decay convinced physicists that another particle, a very light neutral particle called the neutrino, must exist.

The year 1940 marked the end of an era. A different sort of new particle was discovered in cosmic rays, was symbolized by the Greek letter π, or pi, and now called the pion. It really was something new. It was not similar to an electron, as the muon was. It was not anything like protons or neutrons. What could it be? Perhaps it was the so-called Yukawa particle.§ The pion was only the first in a great number of new particles that have been discovered. The plethora of particles destroyed the apparent simplicity of a universe constructed only of protons, neutrons, and electrons.

The Chart of Fundamental Particles and Interactions [Fig. 1.4] shows several more of these new particles. We shall investigate some features of the Chart in Chapter 2. For now, we will summarize some of the main features of the structure of matter.

There are two fundamental types of particle found in Nature—*fermions* and *bosons*, as we shall explain in some detail in Ch. 34 and Ch. 39. The proton and the electrons are types of fermion. In the ‘forties, new types of particles were found. The first of these particles discovered were designated π^+ and π^-; these are the pions referred to above. Soon, many other particles similar in behavior to pions were found. They were all bosons. Other bosons, different in nature from the pions, are the *gauge bosons*: the photon, the particle of light, and the W^+, W^-, and Z^0 that were first observed in the early ‘eighties.

Given the obvious great difference between protons and electrons, it is not unreasonable that the fermions are further subdivided into *leptons* (including the electron and its associated neutrino, the muon and its associated neutrino, and a particle known as the tau along with its associated neutrino) and *baryons* (including particles such as the proton and neutron). The leptons are generally rather low in mass; indeed, their name stems from the “lightness” associated with their masses. The baryons’ masses are greater; the

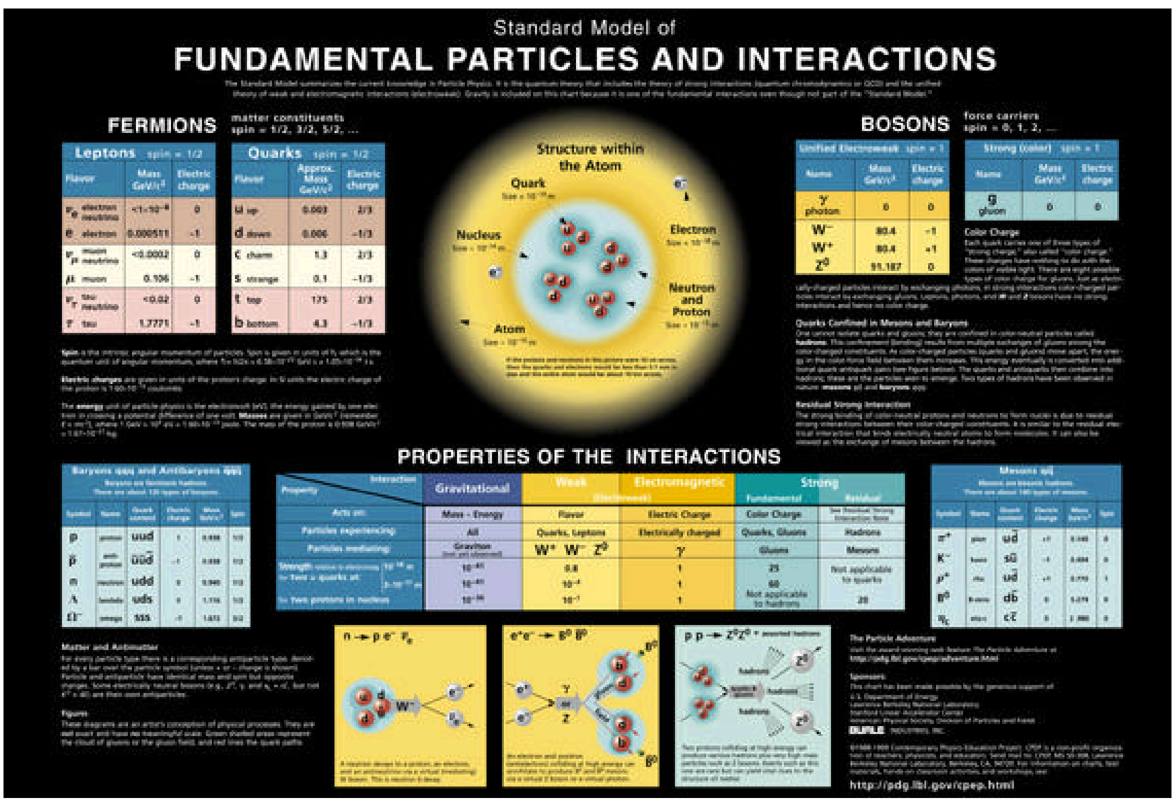

Fig. 1.4 Chart of Particles and Interactions.

root of the name baryon is based on the Greek word for “heavy.” The pion-like particles, midway in mass between leptons and baryons, were called *mesons*, from a Greek word for middle.

§ The theoretical physicist Hideki Yukawa had already developed a theory during the 1930s that called for a particle to exist that would bind the protons and neutrons together inside the nucleus. See Chapter 2 for further discussion of Yukawa’s idea.

One thing that was soon noticed is that all leptons more massive than the electron will decay until they produce an electron. Similarly, all free baryons will decay until they produce a proton. All mesons decay rapidly. Impermanence rather than permanence seems a hallmark of Nature at the level of these particles.

Experiments with hadrons have shown that two fermions can get together to make a particle that have the properties of a boson. Likewise, two bosons could get together to make a more massive boson, but could not make a fermion. These results suggest that there is a sublevel to some of the many particles; it must be that the constituents are fermions. In this way, combinations of fermions could make more fermions and make bosons, too. It is possible to construct the properties of all the known baryon and meson particles out of the combination of "basic" fermions. These six basic fermions are known as *quarks*. Experiments involving scattering of particles on other particles led to regularities explicable in terms of the underlying quarks. Some details of the properties of quarks are shown in the Chart [Fig. 1.4].

The leptons remained in a group apart. They appear to be a different kind of particle in their own right. They cannot be made out of quarks, nor can quarks be made out of them. They participate in different kinds of interactions (see Chapter 2).

The six types of quarks and the six kinds of leptons appear to be the constituents of the particles. These particles seem to be organized among themselves into three groupings of two quarks and two leptons each.[§] This replication of three groups is the modern sequel to the puzzle of the existence of the muon. Particle physicists today are still struggling with the modern version of Rabi's question: "Who ordered that?" Nevertheless, the reduction in the number of basic particles to three sets of four has reduced the apparent complexity of Nature once again. Succeeding chapters will follow the story of experimentation, as the evidence supporting these statements is found.

Example 1.10
Use the Chart of Fundamental Particles and Interactions (Fig. 1.4) to classify the following particles:
a) the electron,
b) the tau neutrino,
c) the D^+ particle;
d) the W^-, and
e) the antiproton.
Which of these particles are composed of quarks?

a) The electron is a fermion and a lepton, and is not composed of quarks.
b) The tau neutrino is a fermion and a lepton, and is also not composite.
c) The D^+ particle is a boson, a hadron, and a meson, and is composed of quarks.
d) The W^- is a boson, and is neither a lepton nor a hadron. It is not composite.
e) The antiproton is a fermion, a hadron, and a baryon, and is composed of quarks (actually anti-quarks).

1.6 Two thousand years of simplification

In the last several sections, we have examined the progress in the understanding and classification of matter from the Greeks to the modern age. The vague beginnings (Earth, air, fire, and water) dominated thought for over a millennium. The questioning attitude that arose in the Renaissance led to the rise of science—the idea of the centrality of experiment and the falsifiability of the scientific description. This new attitude led to the modern idea of molecules as constituents of compounds and atoms as constituents of molecules. By analogy and experiment, atoms were found to be built of constituents, and these constituents were particles among many. In a period of a little over 2000 years, we have come to a particle constituent picture that arises again and again. This gives us a picture of the effect of the scientific attitude in the approach to Nature.

[§] The groupings are of the u and d quarks with the electron and its associated neutrino; the c and s quarks with the muon and its associated neutrino; and the t and b quarks with the tau and its associated neutrino. While none of the quarks can be observed outside of the innards of particles, their presences have been indirectly observed in experiments except in the case of the t quark.

At this point it may seem to you that all we have succeeded in doing is to assign names to the particles of Nature. The naming of phenomena is an important part of science because naming something is one of the first steps to understanding. Well-thought-out naming schemes can lead scientists to develop an organization. The names tell us something of the structure of a particle. This in turn can lead to an increased understanding of a phenomenon, to new proposals that lead to new tests. We will see that the name also tells us the type of interactions that the particle can experience.

Physicists present physics at times as a group of laws of Nature. This implies that the laws have been tested and found adequate to describe aspects of the world. But this does not imply that we understand everything. A most important outcome of a validated theory or law is the understanding of its limitations. Perhaps the greatest fascination of physics for physicists is that it is still incomplete. Most physics remains still to be discovered. Physicists can use their curiosity to investigate the subject on the frontiers of change. Fig. 1.5 shows the structure of physics knowledge, as it currently exists.

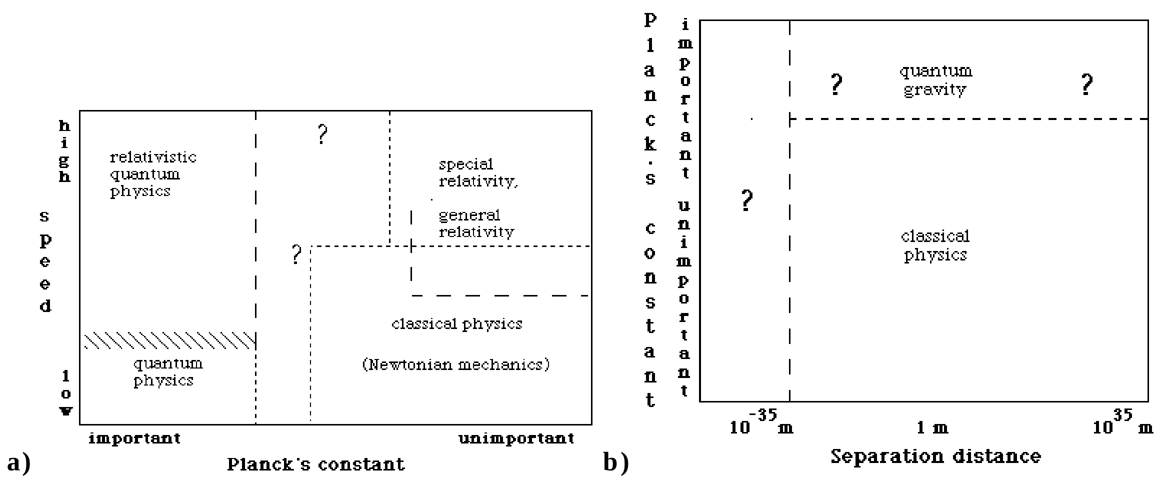

Fig. 1.5 Physics knowledge is incomplete. At the frontiers, new physics will be discovered. a) Knowledge in terms of Planck's constant (the parameter of quantum mechanics) and speed. b) Knowledge in terms of Planck's constant and separation distance.

As always, it is experimentation that will lead to the recognition of the structure both in terms of the types of particles and in the types of interactions. The experiments have led us to a model of the structure of the baryons and the mesons. There are convincing reasons to believe that there is a substructure to the many new particles that have been discovered in the last three decades. Experiments in which "test particles" are smashed into these particles show evidence of the structure lurking within. The regularities we see are attributed to the new substructure of particles called quarks.

The quarks and leptons are currently thought to be fundamental. So were the proton, neutron, and electron in the 'thirties. So were the atoms in the eighteenth century. This sort of prejudice has changed quickly in the past as new layers of structure were found. The quarks fall in families, and the families of quarks and associated leptons are the basic building blocks of our world.

We shall look at the applicability of the details of the structure and behavior of matter, both singly and in combination, throughout this book. It is natural, having all these particles, to turn first to consider the way these particles influence one another. This is part of the subject of the next chapter.

SUMMARY

Physics is a branch of natural science. The root of the word science means “knowledge.” Physics attempts to understand the regularities of the way the world works at a fundamental level. It uses observed facts to test models of reality. Many students look at physics (and all science) as a bunch of facts, but the facts are really secondary to physicists. The organization supporting the experimental observations is far more interesting to them. Facts based on observation are good testing grounds to see how accurate the understanding is.

One place where scientists (and physicists in particular) demand accuracy is in the use of descriptive words. Each word used scientifically has a scientific meaning. The classification of phenomena, *taxonomy*, is one of the bedrocks of science. We need to name something before we can encompass and understand it.

Science attempts to answer some of the “how” questions. It looks for descriptions of the part of reality we can experience directly or indirectly. The most exciting thing about science is that each answer leads to more (and usually more interesting) questions. Science is methodical. Some scientist proposes a model of reality. This might be a small change or a revolutionary change. The same sorts of experimental questions are asked over long periods of time by many investigators about models of reality; after enough confirmatory measurements, the model might be classified as a theory. After still more experimental confirmation, the theory might become a law. However, no matter how many tests confirm what was expected, that does not prove a model correct. Just a *single* observation of a problem with a model can be enough to show that it is in need of replacement or readjustment. Scientific models are subject to being thrown away if they cannot describe the reality we observe; we say that they are *falsifiable*.

The chief distinguishing characteristic of science, which developed in the Renaissance, is its skepticism (its show-me attitude) and its reliance on experiments with Nature as the final arbiter of whether our descriptions are useful. The distinction between science and technology is that science strives for pure knowledge for knowledge’s sake. Technology strives to make something useful from the knowledge that humans have.

It is in our perception of the structure of the world that modern thinkers differ from the ancients. A central characteristic of the Nature physicists have been observing is its granularity, or particulate nature. A building is made of building blocks. Chemists of old knew how to mix the bricks and fire them. These building blocks are in turn made of smaller building blocks (molecules, also studied by chemists), which in turn are made of smaller building blocks (atoms, studied by both physicists and chemists), and so it goes. Physicists have spent the twentieth century studying atoms and the substructure of atoms, the particles within that are combined together to make everything material that we observe.

This “wheels within wheels within wheels” view of Nature is quite different from the views of, for example, the Greek philosophers. This book will emphasize the particulate nature of matter and energy. Again and again, this particulate nature of the world will be seen to have an effect both in the way we view what happens, and in the effects described.

Exercises

1. List some ideas you were told were true, but that later turned out to be false. How did you discover the ideas were false? Examine your experience to see whether your thinking reflected what you might now call scientific principles.

2. Explain the role of prediction in science.

3. Some toys reinforce the idea that the world is composed of basic parts. Can you list some of these toys?

4. Attempt to classify everyday things in terms of the Greeks' four elements [earth, air, fire, and water]. This classification scheme lasted for about 2000 years. Why do you think that the Greeks and their intellectual descendants were satisfied with this scheme for so long?

5. The Greeks ignored atomistic ideas proposed by Democritus and Leucippus.
a) Explain why no Greek philosopher took Democritus's and Leucippus's proposal of the atomic nature of Nature seriously.
b) Explain why their ideas were not testable during their times.

6. *Taxonomy* is the systematic naming and classifying of objects or abstractions from Nature. Explain the role of taxonomy in science. Is all science at least partly taxonomic? Could science have developed without taxonomy? Give an example from some realm of science of the use of taxonomy.

7. Chemists organize the naming of chemical compounds. What would you guess the reason for calling compounds ketones or aldehydes is? What could be similar about methane and ethane? benzene and toluene?

8. Which of the following is a falsifiable theory and which is not? Suggest a method to test each falsifiable theory.
a) The moon is made of green cheese.
b) The proton is formed of constituent particles.
c) The light in your refrigerator stays on after the door is closed.
d) Dirty laundry will spontaneously generate mice.
e) Air has no weight.
f) No more than 246,571 angels can dance on the head of a pin.
g) This book exists, and so do you.

9. Construct some falsifiable theories of your own.

10. What is the best procedure if you run into an idea that is contrary to something you believe?

11. If the electron were discovered tomorrow to be composite [made up of two or more constituents], would this discovery invalidate today's understanding of Nature?

12. Atoms consist mainly of empty space. How is it possible for you to pick up this book if it is mostly empty space?

13. Some things can be thought to be <u>almost</u> true. Can you think of any? To what degree can something be almost true?

14. Explain how the three clearly distinguishable particles π^+, π^0, and π^- can be thought of as members of one family. That is, which of their properties might you expect to be the same if they *are* actually members of one family of particles?

15. How does taxonomy, or naming of things and ideas, fit into the story of the discovery of substructure of matter?

16. Why might scientists observing each generation of the evolution of the understanding of the structure of matter have been satisfied that they had found the lowest level? (You might think about the interplay of the particles with the interactions seen on the Chart. For example, chemistry has to do with the electromagnetic interaction; the study of particles with the strong interaction.)

17. Use the Chart of Fundamental Particles and Interactions to classify the following particles:
a) the photon,

b) the Λ particle,
c) the gluon, and
d) the ρ^+ particle.
Which of these particles are composed of quarks?

18. Use the Chart of Fundamental Particles and Interactions to classify the following particles:
a) the muon,
b) the electron neutrino,
c) the η_c, and
d) the K^- particle.
Which of these particles are composed of quarks?

19. Use the Chart of Fundamental Particles and Interactions to classify the following particles:
a) the π^+ particle,
b) the neutron,
c) the Ω^- particle, and
d) the Z^0 particle.
Which of these particles are composed of quarks?

20. Which of the particles listed in the Chart of Fundamental Particles and Interactions are composed of quarks? Which of these are composed of two quarks? Which of these are composed of three quarks?

21. What is the difference in the structure of the proton and neutron?

22. Explain the role of *facts* in science in general, and in physics in particular.

23. Some physicists believe that there is a substructure to the smallest building blocks of particles that we know. How might these physicists justify this belief?

24. An amateur scientist believes that he has discovered a new explanation of a phenomenon that occurs at particle separation of 1 m, very low speed, and for which Planck's constant is unimportant. He claims that this shows that almost all of conventional physics is wrong. He is selling stock in a company he's starting to apply his new principles. Should you buy stock? Why or why not?

25. Why do physicists consider it advantageous that the structure and knowledge of physics is incomplete?

26. Your seventh-grade sister complains about her science class that she just has to memorize everything and none of it makes sense. What could you say to her to restore her interest in science?

27. Which of the following particles would a particle physicist think are fundamental? Why or why not?
a) W^+
b) the photon (γ)
c) the charm quark (c)
d) the muon (μ)
e) the pion (π)

28. How would a natural philosopher (the old name for physicist) answer the question "Why did the Tacoma Narrows Bridge collapse?"? What is different about the question "How did the Tacoma Narrows Bridge collapse?"?

29. Look up *theory* in the dictionary. How many meanings does this word have? How many of these meanings are consistent with a scientific meaning of the word? Can you identify synonyms that are scientific? Can you identify synonyms that are contrary to the scientific meaning of the word? List several.

30. Justify the view that the words "science of religion" are internally inconsistent, self-contradictory. Justify the contrary proposition. How do your opposing justifications depend on different meanings of the same word?