CHAPTER 1

Atoms to Stars: Scales of Size, Energy, and Force

The microbe and the elephant: the hierarchy of size

Energy and stability

The four forces

Atoms and the periodic table of elements

Seeing atoms: the scanning tunneling microscope

As we look around us we see a world that is marvelously ordered and organized. Outward from the earth we see the moon, the planets, and the stars. Light comes to us from them, and other kinds of radiation, signals that tell us how they look, how big they are, and what they are made of.

We can also go in the other direction, down to smaller and smaller sizes, until we come to pieces that are too small to see directly. They too can be studied by the radiation that they give off, or through microscopes, or, more indirectly, by bouncing other particles off them. As we continue, we get to the atoms that were once thought to be the smallest, the ultimate building blocks. Today we know that atoms have their own structure, each with an even tinier nucleus in the center, with electrons racing around it.

How is the world organized, what can we know and understand about its order? What is it made of, how are its pieces held together, on the earth, out to the stars, and down to the tiniest pieces that we know? How do we find out and how do we learn more? These are some of the questions that we will explore.

The sun, the planets, the atoms, and the nuclei are very different, most obviously in their size. That allows us to study them quite separately, almost as if each existed alone. But no part of the universe is alone. Each is acted on by *forces*, as its neighbors push and pull. In spite of the enormous variety that we observe, it seems that there are just four kinds of fundamental forces. They are the gravitational force, the electromagnetic force, and two kinds of nuclear forces. Each reigns supreme in its own realm. Together they cooperate to create the world that we know, from nuclei to stars, with our own, the human scale, right in the middle.

1.1 The microbe and the elephant: the hierarchy of size

Cut an apple in two. See the flesh, the peel, the seeds. Each is separate, each has its own existence and its own function. The peel provides a barrier against the outside; the flesh protects the seed, which, in turn, waits to play its part when its time comes.

The parts may be separate, but they are not independent. Each depends on the others, each develops from the same seed.

There is an order in space, and an order in the sequence of time. This is what gives order and sequence to our perception and our understanding. We first see the different components separately, and only later ask how they change each other and interact with each other and their environment.

We can cut the apple further, into smaller pieces. How long can we continue before what we have is no longer recognizable as a piece of apple?

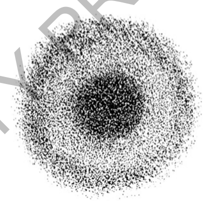
Democritus, more than 2000 years ago, asked that question, and thought that there must be a limit, a point beyond which we cannot continue, when we have arrived at a piece that cannot be cut further, the *atom*, the not-to-be-cut.

Today we know that he was both right and wrong. The atoms are the building blocks of which all materials are made. But we can go further. Each atom has its own structure, with its nucleus deep inside and its electrons around it.

The first one who thought in detail about what an atom might be like with a nucleus surrounded by electrons was Niels Bohr in 1913. He imagined a picture, a "model" of the atom, with precisely known forces and exactly predicted motions of the electrons. It was so successful that it still colors a lot of talk about atoms, even though some of its most important features are incorrect.

Bohr's picture of an atom had electrons circling the nucleus, pretty much as the planets travel around the sun. But an atom is not a planetary system, with electrons moving in fixed and predictable paths. One of the great insights stemming from the development of *quantum mechanics* in 1925 is that the laws governing atoms are different from those that are followed by the sun and the planets.

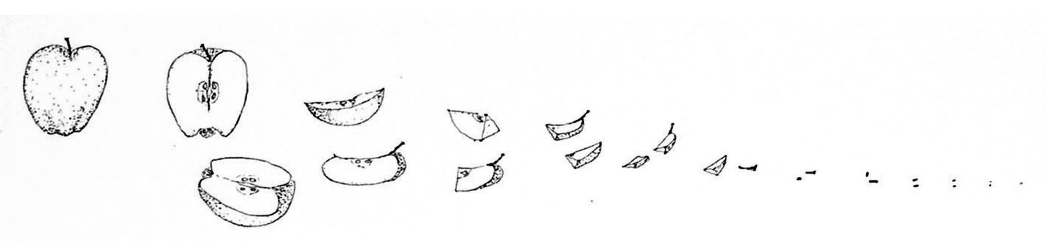
Electrons can be observed surrounding the nucleus, but we can no longer talk about them as moving in circles, or ellipses, or in any other definite path. With the methods of quantum mechanics we can, however, calculate how likely the electrons are to be observed at any particular distance from the nucleus.

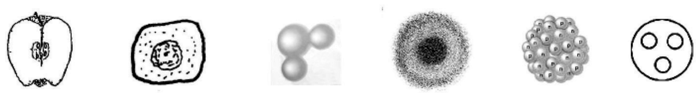


The figure shows the kind of picture that we have. Here a high density of dots represents a high probability that an electron can be found there. There is a simple relation between Bohr's model and the quantum mechanical picture. Bohr said that the electrons had to circle the nucleus at certain definite distances. The new picture says that electrons can be found at other distances, but that the highest probability is that they are observed close to where Bohr said they had to be.

As with the apple, we can study the nucleus alone, and separately the dance of the electrons. The two are distinct, but each is linked to the other, and is rarely without it.

There is further structure within the nucleus, where there are two kinds of *nucleons*, the *protons* and the *neutrons*. In turn, each nucleon





consists of three *quarks*. As far as we know, however, the quarks are locked inside and cannot exist independently.

The figure shows schematic representations of an apple, a cell, a molecule, an atom, a nucleus, and a nucleon.

There is also further structure as we go outside the apple, to the tree, the earth, and the solar system in which the earth is just one of the planets, to the galaxy in which the sun is one of myriads of stars, and to the clusters of galaxies, as we come to the limit of the known.

EXAMPLE 1

(a) How much bigger is our planetary system than the sun at its center: what is the ratio of the diameter of the orbit of Pluto to that of the sun?

(b) What is the ratio of the diameter of a hydrogen atom to that of its nucleus?

Ans.:

(a) Pluto travels about the sun in an elliptical orbit. Its farthest distance from the sun is 7.38×10^{12} m and the closest is 4.45×10^{12} m. The average radius of the orbit is about 5.9×10^{12} m. (10^{12} is the number "1." with the decimal point shifted 12 steps to the right, i.e., followed by 12 zeros. If you're not sure about using this notation, look at the section called "Numbers, huge and tiny: powers of 10" in Chapter 2. In the same chapter there is also a section called "Quantities and units" and one called "Precision: significant figures." Please read them!)

The sun's diameter is 1.39×10^9 m. The ratio of the two diameters is

$$\frac{(2)(5.9 \times 10^{12})}{1.39 \times 10^9} = 8.5 \times 10^3 \text{ or about } 8500.$$

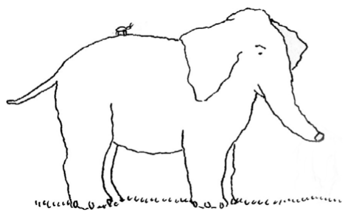
(b) The radius of the smallest orbit of the electron in a hydrogen atom, according to the Bohr model, is 0.53×10^{-10} m. (10^{-10} is the number 1.0 with the decimal point shifted 10 steps to the left, while filling the empty spaces with zeros.) Although the Bohr model is an obsolete representation of the atom, the Bohr orbit's size gives a good approximate number for the atom's size. The nucleus of an ordinary hydrogen atom is a proton. What we call the size of the proton depends on what property is measured, but it is about 10^{-15} m. The ratio of the radii, and therefore also the ratio of the diameters, is 5.3×10^4 or about 53,000.

Here is a table of some distances: from Pluto's orbit to the nucleon size. (The radii are averages.)

Radius of Pluto's orbit	5.9×10^{12} m
Radius of earth's orbit	1.5×10^{11} m
Radius of moon's orbit around the earth	3.84×10^8 m
Radius of sun	6.9×10^8 m
Radius of earth	6.38×10^6 m
Radius of moon	1.74×10^6 m
Human size	2 m
Diameter of human hair	2×10^{-4} m
Red blood cell	10^{-5} m
Escherichia coli bacterium	2×10^{-6} m
Rhinovirus	2×10^{-8} m
Radius of uranium atom	1.4×10^{-10} m
Radius of hydrogen atom	5.3×10^{-11} m
Radius of proton	0.9×10^{-15} m

We know what is between the sun and its planets. Not much. (There is about one atom per cubic centimeter in interstellar space, and perhaps 10 times as many within the planetary system.) The space between the nucleus and the electrons in an atom is very much smaller, but it is even emptier. When we hold something in our hands, a stone, a book, whatever is there, whatever we see or feel, the overwhelming amount is empty space.

Our planetary system as a whole is so much larger than the sun that we can think of the two quite separately. What happens to the earth or the other planets has almost no influence on the sun. It is like microbes on an elephant, or for that matter, in ourselves. They live in their own world, unseen, unthought of, by the world of their host.



The same is true about the size difference between an atom and its nucleus. That's why we can think of the two as separate and distinct—not independent of each other, but each following its course on a vastly different scale. Similarly, each planet travels along its path, unaffected by anything that may happen to one or a few of its atoms, or even to one of us, walking on it.

We are somewhere between, so that on the one hand we think of atoms as invisibly small, and on the other hand of the sun, the planets, and the stars as vast and vastly far away. Each of these systems is to a great extent outside our direct experience, yet each is visible, at least indirectly. Each is known, at least in part, and is being explored in more and more detail.

When all the atoms in a material are of the same kind, it cannot be decomposed into other substances. It is an *element*. But atoms are not usually alone. One way for them to combine is to form molecules. The simplest are the combinations of two atoms of the same element, as in oxygen and nitrogen. These two elements make up most of the air that we breathe. In the air the oxygen and nitrogen molecules fly around separately at great speed. A water molecule consists of three atoms, one of oxygen and two of hydrogen. Other molecules can have many more atoms, especially the organic molecules of living matter, which often consist of hundreds or thousands of atoms.

It is the nucleus that decides which element we have. It does that by the number of protons in it. A nucleus with just one proton is a hydrogen nucleus, with two it is helium, with eight it is oxygen, with 29 it is copper, with 50 it is tin, and so on. We see a wonderful order, with families of elements that have similar properties, with each kind of atom, each element, in its place in the *periodic table of elements*.

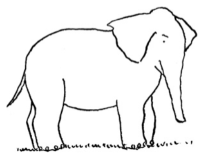
Molecules can be separate, as in air and other gases. They can also combine to form liquids, as in water, or solids. But many solids do not consist of molecules. Their atoms can be in an irregular, or *amorphous* arrangement. More often the atoms form a *lattice*, in which each has its special place. This happens not only in visibly crystalline materials, such as diamond, but also in many others, where the crystal structure is too small to be easily apparent, for example, in most metals.

In metals the atoms in the lattice do not have all their electrons attached to them. One or more of the electrons from each atom leave their "home" atom, and roam freely throughout the piece of metal. These *free* electrons give the metal its characteristic properties, such as its appearance, its strength, and its ability to transport energy and charge.

The ordered hierarchy and separate identities of nuclei, atoms, planets, and stars provide a plan for our quest toward knowledge. When we study the structure or the motion of a planet we don't need to think of whether there are people, or animals, or even mountains and valleys on it. We can study a nucleus without thinking of what is happening to the atom of which it is a part. Each can be looked at separately. Just imagine how different it would be if the universe were more like an ocean, in which the constituents meld into one another, and are distinguishable only with much greater difficulty.

Where do we fit in? It is no accident that the human scale is huge compared to atomic sizes and tiny compared to the size of the earth. On the one side the human structure is so complicated that each of us must be made of a very large number of atoms and molecules. To have the varied and vastly subtle structures of skin and flesh, tissue and blood, the building blocks must be small enough to be capable of being put together in many different ways.

At the other end, as organisms get larger, there is another limit. Large animals struggle with the effect of their greater weight, which makes it more difficult for them to move and even to stand. We are fortunate not to have the massive legs of elephants.



We can see how the elephant's weight and legs are affected by changing the animal's size. Look at what happens when all lengths are increased by the same factor. If the factor is two, the volume and therefore the weight are multiplied by eight. (If the factor is f, they are multiplied by f^3.) But a leg's strength depends on its cross-sectional area, which goes up by only a factor of four (or f^2).

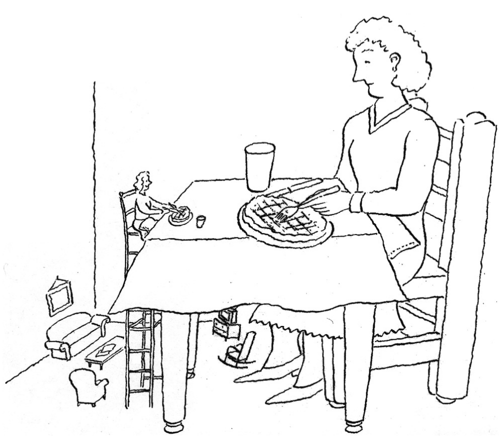
If all lengths increase by the same factor, the leg becomes less able to support the animal's weight. To support the increased weight the leg's cross section must increase by more than f^2. In other words, the leg must become thicker compared to other parts of the elephant's body.

Another factor that is affected by scaling is the energy requirement. Warm-blooded animals lose energy primarily through their surface. The energy that is lost is supplied by the food they eat. As the surface increases by f^2, the volume increases by f^3. The surface-to-volume ratio decreases by f.

EXAMPLE 2

Consider a giant, similar to you, but with linear dimensions that are each 10 times as large.

What are the factors by which each of the following is larger than for you?



length of leg	10
surface area	100
weight	1000
volume	1000
cross section of leg bones	100
weight supported by leg bones	1000
pressure on leg bones $= \dfrac{\text{weight}}{\text{cross section of bone}}$	10
food requirement	100
energy requirement per unit weight	1/10

What might be the giant's attitude toward a steak whose linear dimensions are also each 10 times those of a one-pound steak that you might eat?

"This 1000-pound steak is about 10 times as large as what I need for the rate at which I lose energy through my skin. Also, I don't move around much, since my bones are only a tenth as strong as yours compared to my weight. They are close to breaking when I stand up. My heart is 1000 times as heavy as yours, but since I don't use as much energy my heart rate is much less than yours. That may make me seem sluggish, and has given rise to the image of giants as not so smart. Actually I'm a lot smarter than you. My brain has 1000 times the volume of yours, and therefore has much more room for *neurons*, the threads that provide the pathways for the electric signals that are responsible for sensory perception and thought processes."

These features give only a partial indication of changes with scale. The actual changes in animals with different sizes and weights are more complex. For example, "Kleiber's law" is an empirical relation that says that the resting metabolic rate (the rate of energy expenditure) of similar animals is proportional to $M^{\frac{3}{4}}$, where M is their mass.

1.2 Energy and stability

So far we have concentrated on size. There is another measure that distinguishes the various realms. How hard is it to break apart a solid, a molecule, an atom, or a nucleus? The quantity that tells us how hard it is to carry out each of these transformations is the *energy*.

We can tear a piece of paper, we can break a twig of wood. With a saw we can divide a plate of iron. In each case the material remains the same.

We haven't changed from paper, wood, or iron. We haven't changed the molecules, the atoms, or the nuclei of which they are composed.

Can we change all of these? Yes, but it gets harder and harder, and takes more and more energy, as we go down the scale to smaller and smaller pieces. Changing the molecules is the easiest. That happens when we burn the paper or the wood, or when the iron rusts. In each of these cases oxygen combines with some of the substance that is there to begin with. In each case the atoms remain, but they combine in different ways. That's what happens in a chemical reaction.

Now look at an atom. It consists of a nucleus surrounded by electrons. The electrons are attracted to the nucleus. Usually the number of protons in the nucleus is the same as the number of electrons. The atom is then *neutral*. It is possible to pull off an electron or to add an extra one. The atom is then an *ion*. The number of protons is no longer the same as the number of electrons. That happens when electrons jump between our hair and a comb or between our shoes and a carpet. We can sometimes tell because the electrons will tend to jump back, and may then produce a spark that we can see or feel.

Transforming an atom into an ion (*ionizing it*) has changed the atom, but not the nucleus. That is much harder. If we can do that we can change one element into another. It takes energy to ionize an atom. It takes much more energy to change the composition of a nucleus.

The alchemists wanted to do that. They wanted to change the relatively common element mercury into gold. They failed, but in the process they helped to develop the field of chemistry. Today we know that they weren't so far off in their thinking. The mercury nucleus contains 80 protons, and the gold nucleus 79. We also know how to transform one into the other by a *nuclear reaction*. It requires expensive machinery (like a *cyclotron*) to produce a very small amount of gold, and therefore it isn't the way to get rich that the alchemists had hoped for.

A molecule can be changed by a chemical reaction. An atom can lose or gain electrons. A nucleus can be transformed by a nuclear reaction. But it takes 100,000 to a million times as much energy to change a nucleus as it does to change an atom. That's why we can, most of the time, talk about an atom as if it contained a stable, never-changing nucleus, and hence about the elements as the unchanging constituents of matter.

The binding energy of an object is the amount of energy that is required to take it apart. We can talk about the "total" binding energy, which is the energy required to separate it into all of its pieces. We can also consider the energy required to remove just one piece.

The binding energy of an electron in an atom is the amount of energy that has to be given to the atom to remove the electron. This is also called the *ionization energy*.

The *joule* (J) and the *electron volt* (eV) are units of energy: 1 eV = 1.6×10^{-19} J. (One joule is approximately the amount of energy that it takes to raise an object whose weight is one pound to a height of 9 inches. More exactly it is one newton-meter, i.e., the amount of energy used by a force of one newton to move an object through a distance of one meter. We will look at energy and its units in more detail later.) Electron binding energies are usually measured in eV, nuclear binding energies in millions of electron volts, MeV. (1 MeV = 10^6 eV.)

For the electron in a hydrogen atom in its usual condition or "state" (called the *ground state*) the binding energy (or the ionization energy) is 13.6 eV.

In atoms with more than two electrons the electrons are arranged in shells and subshells. The outer electrons are easiest to remove. In a neutral lead atom, for instance, with its 82 electrons, the easiest electron to remove has a binding energy of about 18 eV. The electrons nearest to the nucleus, which are the hardest to remove, have binding energies of about 88,000 eV.

The total binding energy of a nucleus is the amount of energy required to separate it into all of its nucleons. The binding energy per nucleon is the total binding energy divided by the number of nucleons.

If the total binding energy of a nucleus is higher, it takes more energy to decompose the nucleus into its constituents, and the nucleus is more stable.

For a group of nucleons the most stable arrangement is that which gives the largest binding energy per nucleon.

For uranium the binding energy per nucleon is about 7.5 MeV. The highest number is for iron and nickel, with about 8.8 MeV/nucleon.

The simplest nucleus with more than one nucleon is the deuteron, which consists of one proton and one neutron. It has the lowest binding energy, namely 2.2 MeV. The alpha particle consists of two protons and two neutrons and has a binding energy of 28 MeV.

EXAMPLE 3

A given number of nucleons can be arranged in various ways, as a group of deuterons, alpha particles, etc. Arrange the following in order of stability from the least stable to the most stable:

deuterons, alpha particles, iron nuclei, uranium nuclei, separated nucleons.

Ans.:

The quantity that needs to be considered is the binding energy per nucleon.

For separated nucleons the binding energy is zero. Therefore this is the least stable arrangement. In ascending order of binding energy per nucleon the others are deuterons, alpha particles, uranium nuclei, and iron nuclei. The values of the binding energy per nucleon are 0, 1.1, 7, 7.5, and 8.8.

1.3 The four forces

In our examination of the hierarchy from the very large to the very small, we started with the differences in size, and went on to the differences in the amounts of energy that are required for change or disruption. There is still another way to separate the various realms, and that is by the different kinds of forces that play the most important role in them.

We are most familiar with the gravitational force. It acts between us and the earth, with a force that we call our weight. It also acts between the earth and the sun and between the moon and the earth. It was Newton's great insight to realize that it acts between all objects and particles, attracting each to all others. We are normally aware of it only when one of the objects is of astronomical size, such as the earth, but already in 1798, a little more than 100 years after Newton's publication of the law of gravitation, Cavendish demonstrated that it also acts between objects light enough to be held in our hands.

On the astronomical scale it is the dominant force, and determines the paths of the moons and planets, as well as the large-scale structure of the universe, and, to a large extent, the fate of the stars.

It comes as a surprise to learn that there is a far stronger force that determines almost everything that we are aware of, including our very existence, and that of everything around us. That is the electric force. It is intimately connected to the magnetic force, and their combination is called the electromagnetic force.

Our direct awareness of the electric force is rare. We feel it when we get an electric shock, and we know that it is responsible for lightning. But its sweep goes enormously farther.

Our civilization depends, in some places almost entirely, on electricity for light, for heat and cold, for motors, for the many forms of communication from telephone to radio and television, and for information technology in all its variety.

It is, however, in the microscopic realm that the electric force reigns supreme. It holds the electrons to the nuclei to form atoms, and atoms to each other to form molecules, liquids, and solids. Each time we push or pull, we exert electric forces. The pathways along our nerves, as we feel, or see, or hear, or smell, are electrical.

All chemical changes are the result of changes in the way electrons move around nuclei. Even further, this is true as well for all biological processes, at least those that we know sufficiently to come to any conclusions at all about their microscopic nature.

The electrical nature of our civilization is apparent all around us. Each time we switch on the light, or the toaster, or the vacuum cleaner, pick up the telephone, turn on the radio, television set, or computer, we affect the motion of electrons. Each electron is so light, so small, that it cannot possibly be detected by our senses. Yet they cooperate, move along wires, and bring about the large-scale, macroscopic effects that we experience.

The electric nature of matter is far less apparent. All nuclei contain protons. All atoms contain electrons. The protons and electrons attract each other. But protons repel other protons and electrons repel other electrons.

We describe that by saying that both kinds of particles are *electrically charged*, and that there are two different kinds of charge: *positive* and *negative*. Each proton has a positive charge and each electron has a negative charge. Positive charges experience forces away from each other. They repel. The same is true for negative charges. But positive charges and negative charges attract. The force of attraction between the protons and the electrons, and the force of repulsion between the protons, and between the electrons, is called the *electric force*. This is the force responsible for the existence of atoms. The force between atoms is weaker, but it is also a manifestation of the electric force.

If there are charges in every atom and nucleus, why are we not more aware of them? The answer lies in the very strength of the force. The protons and electrons attract each other so strongly that we rarely find them separately. We seldom find a piece of material that does not contain equal numbers of protons and electrons, and when we do, the difference is minute.

Although the numbers of protons and electrons are almost always equal, we can shift the particles around with respect to each other. We can cause the electrons to move, on average, a little further away from the protons, or a little closer to them. This is what happens each time there is a chemical reaction.

The energy that changes when atoms and molecules combine or separate is commonly called *chemical energy*. Each such change, whether it is as subtle as in biological processes or as violent as in burning and explosion, is, on the microscopic, atomic scale, a change in electric energy.

With the vast variety of phenomena in the universe, it is amazing that just four fundamental forces are responsible for them. In addition to the gravitational force and the electromagnetic force there are two more, and their domain is the nucleus. One is the strong nuclear force, usually called the nuclear force, and the other is the weak nuclear force, most often simply called the weak force.

As we think of the nucleus, made up of protons and neutrons, it is clear that a special force must hold these particles together. The gravitational force is too weak, the electric force does not act at all on the neutrons, and repels the protons from each other. There must be a force that acts on both kinds of particles, i.e., on all nucleons, and that can overcome the disruptive effect of the electric force between the protons. This is the nuclear force. It is the strongest force that we know, but its range is so short that it acts only between neighboring nucleons. It holds the nucleons together to form the nucleus.

That leaves the weak force. Although it acts on nucleons and electrons, it is usually far overshadowed by the other forces. Because of it, however, some nuclear phenomena can occur that would be impossible without it, and they turn out to have profound influences on the universe. The weak force determines the timing of the life cycle of the stars, hence the existence of planets, and ultimately the conditions that make it possible for life to exist.

The difference in scale between the solar system, the atom, and the nucleus is reflected in the differences between the forces that dominate each realm. Each planet is held in its orbit by the gravitational force between it and the sun. The electrons and the nucleus are held to each other in the atom by the vastly stronger electrical force. The still stronger nuclear force acts between the protons and neutrons in the nucleus. The feeble weak force comes into its own in some special situations, which include some that help to control the pulse of the universe.

This brings us to one more surprise, one more insight unimagined before the twentieth century. The path from nucleus to atom, through us and the planets to the stars, is joined at the ends. It is the reactions between nuclei in the sun and the other stars that cause them to release their energy, the energy that radiates to the planets, that has brought about life, and that sustains our existence.

1.4 Atoms and the periodic table of elements

Although the concept of indivisible atoms as the building blocks of matter has been around since the time of the ancient Greeks, until the nineteenth century it was not based on experiments, and had not developed into a theory capable of analysis of known facts or the prediction of new ones.

The closely related concept of *chemical elements* developed gradually during the seventeenth and eighteenth centuries. By the end of that time it was generally accepted that there were elements, like oxygen, hydrogen, sulfur, and a number of metals, that could not be decomposed into other substances.

The two concepts were combined by John Dalton (1766–1844), starting in 1808, into a coherent scheme with many of the properties that are fundamental to modern chemistry. These include that elements are composed of atoms that are alike, that chemical compounds consist of what we now call molecules, each composed of two or more atoms, and that in a chemical reaction atoms are rearranged, but not created or destroyed.

At the same time some of the features of Dalton's scheme show how far his understanding was from today's. He thought, for instance, that atoms were at rest, held in place by repulsive forces between them. He also thought that each was surrounded by a shell of "caloric," the hypothetical substance that was supposed to represent heat.

Dalton's atoms and molecules explained why compounds consist of definite fractions of elements, as measured by the weights of their constituents. For example, hydrogen and oxygen combine to produce water. In each water molecule there are always exactly two hydrogen atoms and one oxygen atom.

Dalton's scheme led to the concept of *atomic weights*. These were only relative weights, since there was at that time no means of knowing of how many atoms or molecules a piece of material was composed. Knowledge of the size and weight of individual atoms and molecules did not come until more than half a century later, with the development of the kinetic theory of gases.

In the meantime the idea of atomic weights had a striking influence on the progress of knowledge of elements and their atomic structure. Hydrogen was recognized as the lightest element, and in 1815 William Prout, an English physician, suggested that all other elements were multiples of hydrogen. That turned out not to be the case, and Prout's hypothesis was abandoned. From today's perspective it seems remarkably prophetic.

The same idea was carried to a much more fruitful level by Dmitri Ivanovich Mendeleev in 1869. He ordered the known elements in the sequence of their atomic weights. It was known by that time that there were families of elements like the *halogens*, fluorine, chlorine, bromine, and iodine, and the *alkalis*, lithium, potassium, sodium, rubidium, and cesium, each with a number of common properties. These were partly chemical properties, such as the way in which they formed compounds. *Salts*, for example, are composed of one alkali element and one halogen element, as in table salt, *sodium chloride*. They were also physical characteristics, as for example the sequence of melting points within the families.

When the elements are put in the order of their atomic weights, it becomes apparent that there is a striking periodicity. After the first group of about eight elements, the next ones, in order, belong to the same families.

H = 1							
Li = 7	Be = 9.4	B = 11	C = 12	N = 14	O = 16	F = 19	
Na = 23	Mg = 24	Al = 27.3	Si = 28	P = 31	S = 32	Cl = 35.5	
K = 39	Ca = 40	– = 44	Ti = 48	V = 51	Cr = 52	Mn = 55	Fe = 56, Co = 59 Ni = 59, Cu = 63
(Cu = 63)	Zn = 65	– = 68	– = 72	As = 75	Se = 78	Br = 80	
Rb = 85	Sr = 87	?Yt = 88	Zr = 90	Nb = 94	Mo = 96	– = 100	Ru = 104, Rh = 104 Pd = 106, Ag = 108
(Ag = 108)	Cd = 112	In = 113	Sn = 118	Sb = 122	Te = 125	J = 127	
Cs = 133	Ba = 137	?Di = 138	?Ce = 140	–	–	–	–
–	–	?Er = 178	?La = 180	Ta = 182	W = 184	–	Os = 195, Ir = 197 Pt = 198, Au = 199
(Au = 199)	Hg = 200	Tl = 204	Pb = 207	Bi = 208	–	–	
–	–	–	Th = 231	–	U = 240	–	–

Others had noticed that, and looked for further repetitions. Mendeleev's *periodic table of elements* (shown in the figure) goes further in two ways. He realized that the periodicity is more complicated than a repetition after every eight elements. In addition, he was so convinced of the correctness of his approach that when an element seemed to be missing, he confidently predicted that a new element would be discovered to fill the empty spot. He soon had some major successes. Gallium, germanium, and scandium were discovered and took their places in the periodic table. Others among the roughly 60 that were then known had their places confirmed or adjusted. The periodic table of elements remains a cornerstone of chemistry, and a bridge between chemistry and physics.

Mendeleev's table was entirely empirical. In other words, it rested only on observation, without any knowledge of the underlying atomic structure that it reflects. It was not until the twentieth century that the reasons for its existence, in terms of atomic and nuclear structure, were understood.

The fact that atoms have an internal structure, with a nucleus, was not known until the experiments of Ernest Rutherford and his coworkers in 1911. The realization that nuclei consist of protons and neutrons had to wait for the discovery of the neutron in 1932.

The atomic weight is not even the right quantity to order the elements. Their properties showed that iodine and tellurium, as well as argon and potassium, are not in the right order if their atomic weights are used. It turned out that it is the number of protons, Z, in the nucleus that determines the particular element, and its place in the periodic table. That is why it is called the *atomic number*.

The number of neutrons can vary. Each different neutron number represents a different *isotope*. Some elements have only a single stable neutron number (a single stable isotope) and others have several. When we write ^{16}O, it says that there are 16 nucleons in the nucleus. Eight of them are protons because oxygen is the eighth element in the periodic table. The rest (also eight) are neutrons.

The weight of the nucleus depends on the number of all the nucleons (protons and neutrons) in the nucleus. It is almost equal to the atomic weight, since the electrons are less massive by a factor of almost 2000. Occasionally the atomic number and the atomic weight don't increase in the same order. For example, potassium has one more proton in its nucleus than argon, so that its atomic number is higher, but its most abundant naturally occurring isotope has two less neutrons, and so its atomic weight is less than that of argon. (A modern table of the elements is shown in the figure.)

Here is one more fascinating question: why does the periodic table end where it does? In Mendeleev's day, and until 1940, it was thought

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112		114		116		118

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

that uranium, with its atomic number of 92, was the last element. In that year neptunium and plutonium were made by bombardment of uranium, and identified as elements 93 and 94. Later other "transuranic" elements, with even higher atomic numbers, were made. That requires cyclotrons and other devices that allow protons and other nuclear particles to be accelerated and used as projectiles. As the atomic number increases beyond plutonium, the nuclei become more and more unstable, and live for shorter and shorter times before disintegrating. In fact, no nuclei beyond atomic number 83 (bismuth) are stable. They are *radioactive*, that is, they change into other nuclei by spontaneous nuclear reactions that change the number of protons in their nuclei. Each radioactive transformation proceeds at its own characteristic rate. Some disintegrate very slowly, especially some isotopes of uranium, whose "lifetime" is measured in billions of years.

The two kinds of forces that act between nucleons in the nucleus are the strong nuclear force and the electric force. (The gravitational force and the weak force are too weak to have a detectable effect.) The nuclear force attracts neighboring nucleons to each other. The electric force acts in the opposite direction, repelling protons from each other. While the nuclear force is only effective between neighboring nuclei, the electric force acts over much larger distances, so that all protons in a nucleus experience it. As we look at nuclei with more and more nucleons, the effect of both forces grows. But because the nuclear force acts only between neighbors, and the electric force acts between all protons, the disruptive action of the electric force grows faster, and eventually overcomes the nuclear force that holds the nucleus together. At some atomic number no combination of nucleons can hold together even for a short time, and the periodic table of elements has reached its upper end.

1.5 Seeing atoms: the scanning tunneling microscope

After Dalton's work in the early nineteenth century the existence of atoms was gradually accepted, but remained controversial until the twentieth century. The evidence was indirect, and actually *seeing* atoms remained impossible. Eventually atomic sizes could be estimated to be from one to several tenths of nanometers. (A nanometer, 1 nm, equal to 10^{-9} m, is a billionth of a meter.)

Simple magnifying lenses were known to the ancient Egyptians, and the compound microscope, consisting of two lenses, has been known since the end of the sixteenth century. There is, however, an inherent limit to the magnification that can be achieved by optical means. The wavelength of light is between 400 and 800 nm, so that light is too coarse a probe to be able to detect atoms. Shining light on a surface to see atoms is like trying to see a needle on a football field from a helicopter.

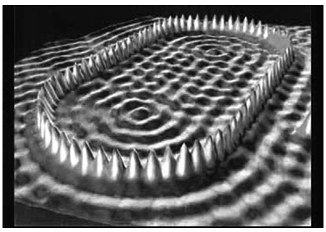
H. Rohrer and G. Binnig. Courtsey IBM Research-Zurich.

In 1981 Heinrich Rohrer and Gerd Binnig built a device based on an entirely different principle, capable of resolving distances of the order of atomic sizes. It depends on the fact that when a metal tip is very close to a metallic surface, electrons can flow from one to the other, as in a very small spark, even when the tip and the surface don't touch. This so-called "tunneling current" decreases very quickly when the distance is increased.

The realization of this instrument depended crucially on very steady and precise positioning of the tip, and on being able to move it in a controlled way along the surface that is being examined. Rohrer and Binnig used the *piezoelectric effect*, that is, the property of some materials, like quartz, to expand or contract when an electric voltage is applied across them.

Since the tunneling current varies so quickly with distance, they used an electric circuit to move the tip up or down so as to keep the current constant as the tip moves along the surface. This vertical motion then follows the details of the electron cloud on the surface, moving up and down at each atom.

Here is an example of a scanning tunneling microscope result. It shows a ring of iron atoms on a copper surface.



(Image originally created by IBM Corporation)

1.6 Summary

We looked at three ways to sort the different parts of the universe: their size, their binding energy, and the forces that predominate.

The sizes that we considered range from the *femtometers* (1 fm = 10^{-15} m) of the nucleons and the nucleus to the billions of kilometers across the solar system.

The binding energy of an object is the amount of energy that is required to take it apart. For atoms it is measured in *electron volts* (eV), for nuclei it is measured in millions of electron volts (MeV). 1 eV $= 1.6 \times 10^{-19}$ J. 1 MeV $= 1.6 \times 10^{-13}$ J.

The total binding energy of a nucleus is the amount of energy required to separate it into all its nucleons. We can also talk about the energy it takes to remove a single nucleon or other particle. It is called the binding energy of that particle.

The force that holds the atom together is the *electric force*. The force that holds the nucleus together is the *strong nuclear force*, sometimes just called the *strong force*, or the *nuclear force*. The *gravitational force* is much weaker. It is responsible for keeping the planets in their orbits around the sun. It is also the force that formed the planets and the stars.

The *weak nuclear force*, usually just called the *weak force*, is the weakest of all. It doesn't hold anything, but it regulates the timing of some important processes, including the life of the stars.

All materials are made up of the *elements*, each with its kind of atoms, starting with hydrogen. Each atom has a nucleus that consists of protons and neutrons. The number of protons in the nucleus is called the *atomic number*. The hydrogen atom has one proton in its nucleus and its atomic number is 1. At the other end of the list of naturally occurring elements is the uranium nucleus. It has 92 protons, so that its atomic number is 92. When the elements are put in order of their atomic number, they form the *periodic table of elements*. It is arranged in columns, each with a family of elements that shares a number of chemical and physical properties.

An element can have different *isotopes*, each with a different number of neutrons in the nucleus. Most properties, however, including the way elements combine (the *chemical* properties), depend only on the atomic number.

The numbers in the symbols ^{1}H, ^{16}O, ^{238}U, etc. represent the number of nucleons (protons and neutrons) in the nucleus. In a neutral atom the number of protons and electrons is the same. An atom with different numbers of protons and electrons is an *ion*.

Individual atoms can be separately detected ("seen") by using a *scanning tunneling microscope*.

1.7 Review activities and problems

Guided review

1. To make a large-scale representation of a hydrogen atom in its ground state, you start with a golf ball ($D = 4.27$ cm) to represent the nucleus. How far away (in km and miles—1 mile = 1.61 km) will you have to put the representation of the electron?

2. Consider a giant similar to the one of Example 3, i.e., with body dimensions most of which are 10 times yours. The legs and leg bones, however, have a greater diameter, so that the giant's body weight, divided by the legs' cross-sectional area, is the same as for you.

(a) How much larger than yours is the cross section of the giant's leg?

(b) How much larger is the leg diameter?

(c) What are the answers to parts (a) and (b) in terms of the scale factor f (which is equal to 10 in this example)?

3. How much energy would it take to decompose a nucleus of ^{238}U, with its 238 nucleons into its separate nucleons? (This is the total binding energy of this nucleus.)

Problems and reasoning skill building

1. You want to draw a picture of the sun and the earth, to scale, on a sheet of paper. To fit it on the paper you start by representing the diameter of the earth's orbit around the sun by a distance of 25 cm.

(a) How large do you have to draw the diameters of the sun, the earth, and the orbit of our moon?

(b) How large a sheet of paper would you need to draw the earth's orbit if you had to represent the earth by a circle whose diameter is 1 mm?

2. The *order of magnitude* of a quantity is its size to the nearest factor of 10. For example, the order of magnitude of the size of an atom is 10^{-10} m.

What are the orders of magnitude of the following:

(a) sizes (in m) of the solar system, sun, earth, moon;

(b) binding energies (in eV) of the hydrogen atom and the deuteron.

3. What are the orders of magnitude of the sizes (in m) of the following:

(a) Highest mountain on earth
(b) Largest animal
(c) Smallest animal
(d) Hydrogen atom
(e) Nucleon

4. (a) How many people, standing on each other's shoulders, would it take to reach the sun from earth?

(b) Name an object so that the ratio of the size of a person to the size of the object is the same as the ratio of the radius of the earth's orbit to the size of a person.

5. For each of the following forces and combinations of forces name one or more objects that are affected by them.

(a) Nuclear but not electric
(b) Electric but not nuclear
(c) Electric and nuclear
(d) Electric and weak
(e) Weak but not electric

6. Which of the four fundamental forces predominates in each of the following cases?

(a) Motion of the planets
(b) Changing colors of leaves
(c) Radioactivity
(d) Digestion
(e) Friction

7. The "atomic" bomb dropped on Hiroshima contained about 60 kg of its explosive material (uranium "enriched" so as to contain more of the isotope ^{235}U than natural uranium). It released an amount of energy equivalent to that of about 15,000 tons of the "ordinary" chemical explosive TNT. Explain the magnitude of the ratio of these two weights in terms of the forces and energies involved in the explosion of the two materials.

8. Which two forces are in competition for the stability of nuclei? Which one holds the nucleus together and which one tends to disrupt it? Why is the disruptive force more important in large nuclei?

9. The atomic number of uranium is 92. How many neutrons are there in a nucleus of ^{235}U?

10. Hydrogen and helium are the first two elements in the periodic table of the elements. What would have to be changed in a nucleus of ^{3}He to convert it to a nucleus of ^{3}H?

11. What is the number of protons, neutrons, and electrons in a neutral atom of ^{23}Ne?

12. Gold and mercury are neighbors in the periodic table of elements. What has to be changed to change an atom of mercury into an atom of

gold? Explain why this is so difficult in terms of the forces and the binding energies.

13. The simplest stable nucleus consisting of more than one nucleon is the deuteron. It consists of a proton and a neutron. It is the nucleus of an atom of deuterium or heavy hydrogen, which is 0.015% of ordinary hydrogen. It takes an energy of 2.24 MeV to separate the deuteron into its two constituents.

(a) What is the ratio of this energy to the energy required to separate the proton and the electron in a hydrogen atom?

(b) What does this problem illustrate about the strength of the forces that are involved and about the relative stability of atoms and nuclei?

14. The binding energy of an electron in a helium atom is 24.6 eV. The binding energy of a neutron in an alpha particle (the helium nucleus) is 20.6 MeV. By what factor is it harder to remove the neutron than the electron? What general feature of nuclei and atoms does this example illustrate?

15. The nuclear force has such a short range that it acts only between neighboring nucleons. The electric force decreases with distance, but quite gradually (as $\frac{1}{r^2}$). Consider a nucleus with 100 protons and 120 neutrons. If one more proton is added, how many nucleons will experience an additional electric repulsion? How many nucleons will experience an added nuclear attraction? As nuclei get bigger, how does the importance of the electric force change, compared to that of the nuclear force?

Multiple choice questions

1. To take apart a nucleus is harder than to take apart an atom by a factor of about

(a) 100
(b) 10,000
(c) 1,000,000
(d) 100,000,000

2. The modern periodic table of elements is ordered by

(a) Atomic weight
(b) Atomic number
(c) Number of nucleons in the nucleus
(d) Number of neutrons in the nucleus

Synthesis problems and projects

1. About what fraction of the volume of the solar system is occupied by the sun and the planets?

2. About what fraction of the volume of an apple is empty space?

Think of this question in steps.

(a) What fraction of the hydrogen atom is empty space? (The electrons may be considered to be point particles that take up no space at all.)

(b) As a rough approximation, what do you expect this ratio to be in other atoms?

(c) What do you expect for the apple?

3. What is it that Mendeleev discovered that led to the first periodic table of the elements?

4. In the periodic table of elements the pairs argon and potassium, and iodine and tellurium are not "in the right order" if the elements are arranged in order of their atomic weights. What does it mean to say that they are not in the right order, and how can you tell?

5. Search the Internet under "Periodic Table of Elements." On several of the tables you can click on the symbol for an element to find its properties.

What is the abundance of *deuterium*? This is the percentage of hydrogen where the nucleus of a hydrogen atom is not a proton, but a *deuteron*, consisting of a proton and a neutron.

6. What are some of the features of Mendeleev's original table that are incorrect? What features are missing?

7. Here is a statement from the text: "The weak force determines the timing of the life cycle of the stars, hence the existence of planets, and ultimately the conditions that make it possible for life to exist." Explain the connection between life on earth and the life cycle of stars.

An excellent discussion of this question is in the article "Energy in the Universe" by Freeman J. Dyson in the September 1971 issue of *Scientific American*. ("The proton-proton reaction proceeds about 10^{18} times more slowly than a strong nuclear reaction at the same density and temperature," implying that if the life cycle of the sun were governed by a strong nuclear reaction it would have burned up long ago.) This issue was reprinted as "Energy and Power"

(W. H. Freeman, 1971). It includes a number of outstanding articles that remain relevant today.

8. Search the Internet under "Scanning Tunneling Microscope." Find the Nobel-Prize lecture of its inventors. Read at least the first half dozen paragraphs.

Was their original aim to build a microscope?

How much bigger is the area that they hoped to get down to than the area of a hydrogen atom? (Other atoms have more electrons and you might expect them to be much larger. But the nucleus then also has more charge and holds the electrons more tightly. As a result the sizes of atoms do not vary very much.)

You may need to know what an Angstrom (Å) is. It is 10^{-10} m. (Also: "spectroscopy" is the study of the possible energies of a system.)

Find and look at the "STM image gallery" (from IBM). It includes the STM image in this chapter.

9. What would be the form of Kleiber's law if the simple scaling described in the giant's soliloquy in Example 2 were followed?