Chapter 1: Introduction to forces

A. When is a force ... a force?

The word "force" often has an intuitive meaning. To describe its properties, a strong spring requires a broad force concept: a spring is an object that can be stretched or compressed by *forces* or, in an equivalent statement, a stretched or compressed spring will exert *forces* on any object it touches. It is very difficult to describe a spring without invoking words akin to force, such as "pull" or "push". We invoke a force known as gravity to describe why a rock thrown upward a given distance will return to earth. We appreciate that, refrigerators, computers and televisions, use electric and magnetic (electromagnetic) *forces*, but perhaps in unfamiliar ways.

Without any obvious source, we can also see quite mysterious effects of forces. In an accelerating rocket or in an orbiting spaceship, an astronaut can experience forces that feel very different from those commonly experienced on earth. These effects are also due to the action of gravitation and electromagnetic forces; the mystery is removed once the true origins of the effects are recognized.

Gravitational and electromagnetic forces are examples of what physicists call "fundamental forces". At the microscopic level, electromagnetic forces between atoms determine the properties of all matter. The behavior of a spring reflects these underlying forces remarkably well. For this reason, in this text the study of forces starts with a focus on the behavior of springs.

In our language, the word force has uses that have nothing to do with physical science. If you were "forced" to do your homework as a child it is likely that your parents used coercion and not physical force. "The Force" from the movie *Star Wars* will not be described in this text, nor will there be a discussion of other "supernatural" forces, telekinesis, metaphysics, or extrasensory perception. On the contrary, the concepts and techniques in this text will help you distinguish between physical science and science fiction.

B. A short history of forces

The purpose of this section is to provide a perspective that reduces the number of fundamental forces to just four, and to emphasize that two of these, gravity and electromagnetism, are responsible for nearly all physical phenomena. Also presented are fundamentals of the scientific method, including the experimental and theoretical requirements for a hypothesis (new theory), such as Einstein's relativity, to be accepted as an improved theory.

The time chart in Figure 1.1 shows a much abridged history of the understanding of physical phenomena from the time of the atomic hypothesis of Democritus (approx. 500 BCE) to the electroweak theory of Weinberg and Salam (1985), with an emphasis on the behavior of forces.

A description of forces by Aristotle, one of the greatest philosophers of all time, remained unquestioned for nearly two thousand years. However, his seemingly logical description of forces gave incorrect predictions for the results of simple experiments. Students using their intuition often make the same errors made by Aristotle (not such bad company!).

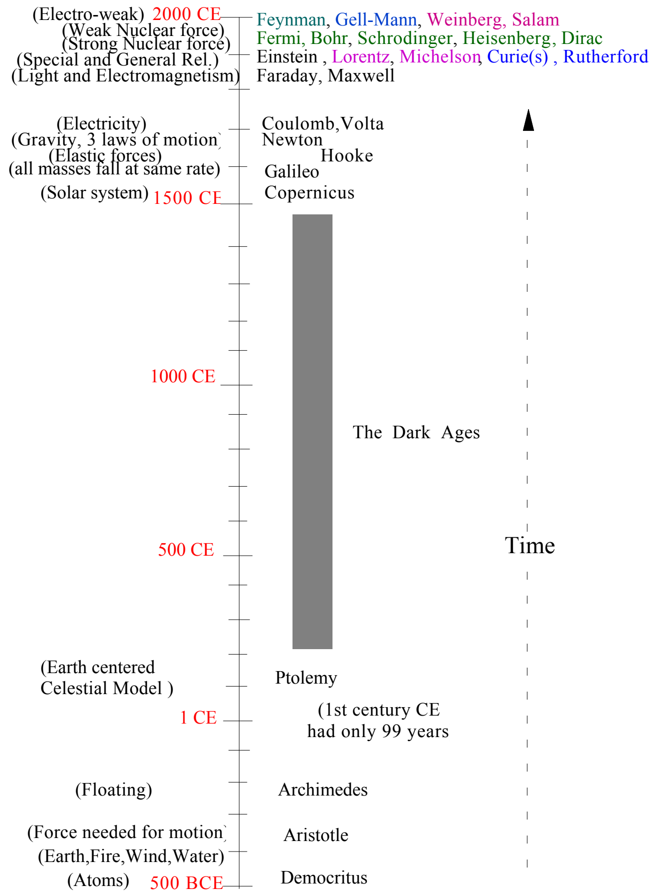

Figure 1.1 Discovery of the physical world by natural philosophers

During and after the Renaissance (1600-1700), natural philosophers (in addition to their other professions), including Copernicus, Galileo, and Newton, found the errors in Aristotle's logic that had hindered scientific progress for so many centuries. Their descriptions of motion, the effects of forces, and the behavior of gravity gave correct predictions for nearly all terrestrial and astronomical observations, and has been known ever since as "Newtonian mechanics"; the subject of this text.

Then, in the first century of the age of invention (1800 to this day), a burst of experimental and theoretical knowledge obtained by Faraday, Maxwell, and others, was remarkably successful in describing the mysterious forces of electricity and magnetism. These forces are related to a feature of matter called electric charge, of which there are three: positive (+), negative (–), and neutral. Two isolated objects with a charge of the same sign (+ + or – –) will be pushed apart (repelled) by a repulsive force and with opposite sign (+ –) will be pulled together by an attractive force. An object with equal amounts of positive and negative charge (uniformly distributed and immobile) appears neutral, and is unaffected by, and does not affect, a nearby charged or neutral object. In 1865, Maxwell uncovered the underlying theoretical connection between electricity, magnetism, and light (electromagnetic waves) and thereby "unified" these forces into the *electromagnetic* force.

It is true, but hardly obvious, that phenomena as diverse as a candle burning in air or a sugar cube dissolving in water are effects caused (primarily) by the electromagnetic force, as are most physical processes, such as those listed in Figure 1.2. Atoms interact with other atoms solely through electromagnetic forces between their charged components (particles called electrons and protons). Any chemical reaction, or matter changing phase, e.g., solid to liquid, reflects the properties of the electromagnetic force.

- pull of a stretched bungie cord
- color of flower
- smell of fresh paint
- melting of ice
- thunder
- bubbles in beer
- causes of a sunburn
- pain of a bad sunburn
- flame of a match
- friction
- effects of aspirin
- perception by a human brain
- explosion of TNT

Figure 1.2 More effects of the electromagnetic force

The principles of Newtonian mechanics and the behavior of the forces of gravity and electromagnetism provided the foundation for the industrial and scientific revolutions that followed. But a discovery was also made implying that Newtonian theory was flawed. Viewed from a moving train, the apparent speed of an object is affected by the speed of the train. Michelson and Morley found, however, that the speed of light was *unaffected* by the motion of the earth around the sun.

This situation was rectified during the period 1905-1915 when Einstein obtained revolutionary insights into the nature of space, time, and gravity. Einstein's theories provided correct predictions in the case of high speed or strong gravity.

> To be accepted, a new theory, such as Einstein's, must: 1) predict those phenomena incorrectly described by the old theory, and 2) show why, in normal circumstances, the old (flawed) theory could give apparently correct predictions.

Usually, the latter condition is the most difficult to satisfy. The extremely small differences between the theories of Einstein and Newton at speeds much less than the speed of light, had been missed, but were found in later experiments.

Many further expansions of scientific knowledge were made during the first 30 years of the 20th century. Atomic structure was realized (electrons, protons and neutrons) and radioactivity was discovered. Also, the quantum nature of light and matter (quantum mechanics) uncovered two new forces with effects observable only at distances comparable to the size of the atomic nucleus (in scientific notation, about 10^{-14} m). *WARNING*, do not skip the review of scientific notation found at the end of this chapter!

One of these forces, the *strong nuclear* force between protons and neutrons, holds the nucleus of an atom together, against the electromagnetic repulsion of the (positively charged) protons. Nuclear forces are responsible for the energy released in the fission (splitting) of uranium nuclei in nuclear power plants, and the energy released in stars from fusion reactions that form helium nuclei from protons and neutrons. The other, the *weak nuclear* force, is responsible for one type of radioactivity, radioactive beta decay, and is always associated with the emission or interaction of a neutral particle called the neutrino (Italian for "little guy") and identified by the Greek letter "nu", ν . After a few billion years in the life of a large star, the weak nuclear force can, in less than a second, form a neutron star with the emission of a truly astronomical number of neutrinos. Neutrinos interact with matter only though the effects of the weak nuclear force so that, except for very rare instances, they can pass completely through the earth without interaction.

Significant progress has been made by physicists in recent years to unify the weak nuclear force with the electromagnetic force and work continues today to include the strong nuclear force and gravity in this unification. If achieved, this would create a unified theory of all forces, showing them to be manifestations of a single, but complex force. In this theory, the various facets of the unified force only become evident as the universe expands and cools (after the Big Bang) to its present average temperature of 3 Kelvin.

The forces of gravity and electromagnetism, however, are primarily responsible for most common phenomena. Particularly important, are the electromagnetic forces generated between atoms of stretched or compressed solid objects. A review of atomic structure is given in the next section where the concept of force is developed further.

C. Structure of the atom

It is remarkable that Newton's laws, Maxwell's electromagnetism, and Einstein's relativity were conceived *before* the basic structure of the atom was uncovered by Ernest Rutherford and his colleagues in 1911. Rutherford's experiments showed that the atom's negatively charged electrons (discovered by J. J. Thomson, 1897) and positively charged protons are not spread uniformly over the volume of the atom.

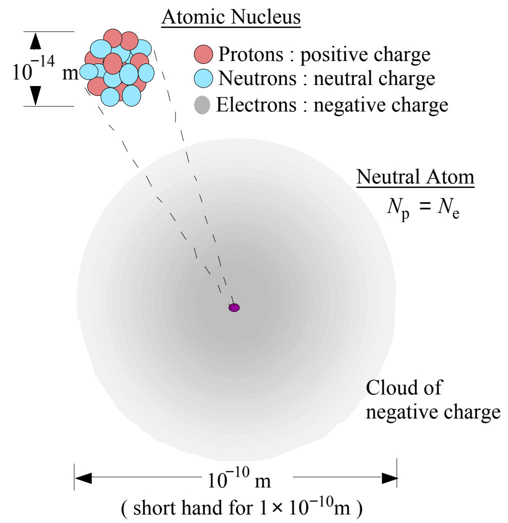

Figure 1.3 A model for the structure of the atom

Instead, as sketched in Figure 1.3, a measurement of the size of an atom determines the approximate extent of a diffuse cloud of electrons held, by the electromagnetic force, in the vicinity of the protons. The protons and neutrons (discovered by Chadwick, in 1937) are confined (bound) by the strong nuclear force to the *atomic nucleus*. The nucleus is a very small region with a diameter of about 1×10^{-14} m at the center of the atom; for this reason protons and neutrons are called *nuclear* particles (*beware*, the central part of a living cell is also called the nucleus). Atoms with the same number of protons but differing number of neutrons are called isotopes of that element.

For an object as small as, or smaller than, an atom, a precise description is possible only in the language of quantum mechanics. The artist's rendition shown in Figure 1.3, however, can be used as a model to discuss the type, number, charge, and size, of the components of an atom. Also, with less accuracy, the model can describe the behavior of neighboring atoms in a solid object.

In an undisturbed atom, the number of electrons and protons, and amounts of negative and positive charge, are equal. Therefore, when viewed from afar, an undisturbed atom appears electrically neutral (net charge zero). Up close, however, one can observe that the electrons are very light (1/2000 the weight of a proton), comparatively mobile and in constant motion, and are occasionally found well beyond the nominal size of the atom. Only electrons can be transferred easily, as shown in Figure 1.4, from one neutral object to another, leaving the former with a positive charge and giving the latter a negative charge (and also transferring the very small mass of the electrons). A positively charged object can be created, only by transferring to other objects the same amount of negative charge. Electrons determine all chemical properties of matter.

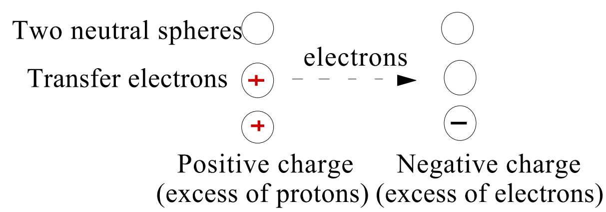

Figure 1.4 Creating a positive charge on a neutral object

Nearly all matter is electrically neutral, even matter within a battery. To emphasize this point, I will dispel a very common misconception about batteries. In a neutral battery, a reversible chemical reaction transfers electrons from a small fraction of the atoms at one pole (labeled +) to the other pole (labeled –), as shown in Figure 1.4, and in the process, increases their energy. When the excess electrons leave the negative pole, through a wire, and return to the positive pole with their energy extracted, the battery is again neutral. Further chemical reactions quickly move more electrons across the battery keeping it ready for use. A battery is "dead", its energy depleted, when the chemicals, needed to move electrons across the battery, are completely reacted.

"Charging" a battery is a misnomer because a battery does not store charge. To charge a dead battery, the original chemical mixture in the battery must be restored. In a car, an electric generator pushes electrons in the opposite direction through the battery, thus reversing the chemical reactions and "recharging" the battery.

D. Molecules and materials

If atoms behaved like neutral billiard balls, nothing special would happen when two atoms were brought close to each other. The electrons of an atom, however, are in constant motion, and near the periphery of the atom they can be influenced by the charge of electrons and protons in a neighboring atom. The atomic model of the previous section can be used to model the forces that occur when two atoms are moved close to each other, however, as with the single atom, only a quantum mechanical description is accurate.

Shown in Figure 1.5 are two oxygen (or other common gas) atoms at various separations. At the top, the atoms are far enough apart so that no interaction occurs between them. When moved closer and released there is a small overlap of the electron clouds and electrons redistribute around both atoms. Between the atoms, due to sharing (interchange) of electrons, the density of electrons is a little larger than obtained from just the sum and results in an electric attraction of the two nuclei toward this concentration of electrons. As the atomic nuclei are moved much closer to each other (as shown at the bottom) the density of electrons in the region between the two atoms becomes smaller than needed to overcome the repulsion of the two atomic nuclei. This causes a net repulsion of the atoms that pushes them toward a larger separation.

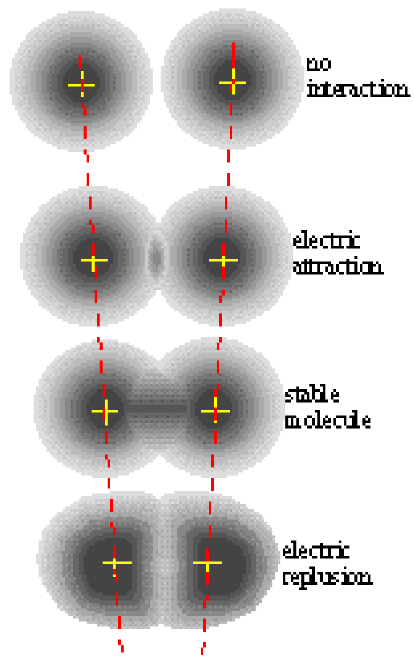

Figure 1.5 A model for the formation of molecules.

Between the two extremes of electric attraction and electric repulsion there is a stable separation, where there is no net attraction or repulsion of the two nuclei. If there is an attempt to move the bound atoms apart, as soon as the separation changes, an attractive force pulls them back toward the original separation. If the atoms are moved closer together, a repulsive force pushes them back toward the original separation. Only at large separations, where the interactions with distant atoms begin to dominate, can the two atoms be considered permanently separated.

At the stable, or equilibrium separation, the atoms form a molecule with a covalent chemical bond. The words bond, bound, and binding bring to mind images of ropes tied tightly around objects. For bound atoms, however, the ropes are loose until the atoms are separated. The binding forces exist only when the separation between atoms is larger than the equilibrium separation. Redistribution of electrons around the atoms, as governed by quantum mechanics, creates *two* states where *no force* (none, zero) acts on either atom: 1) at the equilibrium separation, and 2) when the atoms are far apart. More than two atoms and atoms of different elements can form molecules. Common examples are molecules of water (H_2O, two hydrogen and one oxygen atom) and carbon dioxide (CO_2, one carbon and two oxygen atoms).

Electromagnetic forces of similar origin form collections of molecules (matter), that are found in a particular phase: solid, liquid, or gas, at a temperature and pressure determined by the details of the forces generated between them. Stretching or compressing a solid object will change the separation of each molecule relative to its neighbors and is the subject of the next section.

E. Elastic forces

It is surprising to learn that most solid objects exhibit the properties of, and the forces *generated by*, a rubber band (often referred to as an "elastic" band) or a spring in a retractable ball point pen, or in the suspension of a car. These are all “elastic” objects and the forces *generated by* these objects are known as “elastic” forces. Other forces must be *applied to* these objects to extend or compress them from their normal shape. Elastic objects will return to their normal shape if the distorting forces are slowly removed. Most solid matter, including a concrete walkway, a steel beam, or a piece of plywood, will react elastically when forces (that are not too large) are *applied to* it.

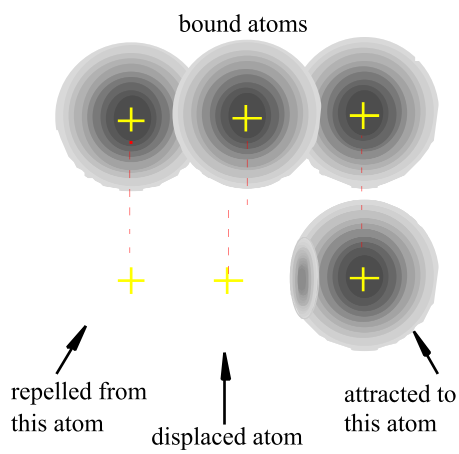

Figure 1.6 Forces on a displaced atom.

As in the system of two atoms of the previous section, each atom or molecule in a solid object is bound to its neighbors by electromagnetic forces that arise *only* if they are moved from their natural locations at the equilibrium separation. In an undistorted (normal or naturally shaped) object, consider the three neighboring atoms shown at the top of Figure 1.6. Each atom is separated from its neighbors by the equilibrium or “natural” spacing.

Assume that the two outside atoms are fixed permanently in their current locations. Move the central atom to the left by an external force (e.g., with your hand) and then release, as shown at the bottom of Figure

1.6. The forces acting on the displaced atom act in a direction that will return it to the original location: the atom on the left pushes (repels) the displaced atom to the right, while the atom on the right pulls (attracts) the displaced atom, also to the right. Both forces act in a direction that "restores" the displaced atom to its natural location.

In an undistorted object the "equilibrium" separation and the natural separation of atoms are the same. In a stretched object, the atoms find a new equilibrium separation along the direction of stretch, where the distance between any two neighboring atoms is made larger by an equal amount. In a squeezed object, the atoms find a new equilibrium separation with the distance between any two neighboring atoms made smaller by an equal amount. Restoring forces push and pull a displaced atom back toward the equilibrium separation.

The state of balanced forces on an atom in an equilibrium position within a distorted object can be described in a personally meaningful way. Imagine that you are an atom and two friends, one on either side of you, hold your arms out to the sides and prepare, but don't yet apply forces to your arms. In this balanced state, no force is applied to either arm, and is analogous to the normal state of an object.

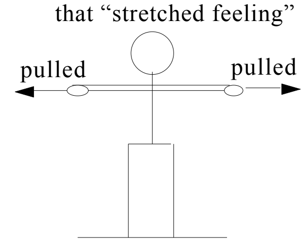

Figure 1.7 A person being stretched by two friends.

If friends pull with on your arms with external forces of equal magnitude, as shown in Figure 1.7, this also results in a balanced state of forces: the amount of force acting in one direction is balanced by an equal amount of force acting in the opposite direction. If you try to move farther from one friend and closer to the other the forces will likely become unbalanced in a way that will tend to pull you back toward the original position, though the friends can, perhaps, do things with their bodies that will modify these results somewhat. The electric forces, however, have no choice but to try to move an atom back toward its equilibrium position. You are quite aware that two forces act because you feel your arms being pulled outward from your body. When both friends simultaneously stop pulling, you loose the stretched feeling. At no time will the forces cause your body to *begin* to move in either direction.

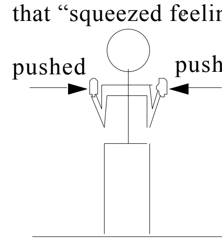

Figure 1.8 A person being squeezed by two friends

If both friends apply equal *inward* forces to you, as shown in Figure 1.8, then you experience a squashed, squeezed or crushed sensation. The forces here are also balanced so that the location of the center of your body does not move, but the body is pressed inward from both sides.

It is not hard to translate these sensations into words that describe the same forces acting on atoms *within* an inanimate object (see Figure 1.9). The feeling of being stretched translates to the word *tension*, while the feeling of being squeezed translates to the word *compression*. These words refer to the forces acting on each atom within the distorted solid object: tension forces act on atoms within a stretched object and compression forces act within a compressed (squeezed) object.

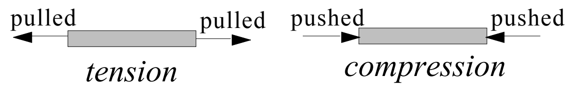

Figure 1.9 Internal forces of tension and compression within matter distorted by stretching (left), or squeezing (right) external forces.

The spaces between atoms in a solid object are small, so that the separation distance between their centers is close to an atomic diameter, approximately 10^{-10} m. When a stiff object is stretched, the distance between atomic centers is changed by only a very small amount. A large number of microscopic changes in the separation between atomic centers, add up in the direction of the distortion to the macroscopic (large scale) change in the shape of the object.

A more visual model of a solid, shown in Figure 1.10, describes atoms as small hard spheres, attached to each other by coil springs that model the behavior of electromagnetic forces between the atoms. These springs, distorted by stretching *and* by compressing, return to their original shape when the distorting forces are removed. A slinky toy or a bungie cord can be stretched but not compressed, therefore, these objects do not have the characteristics of the springs used here.

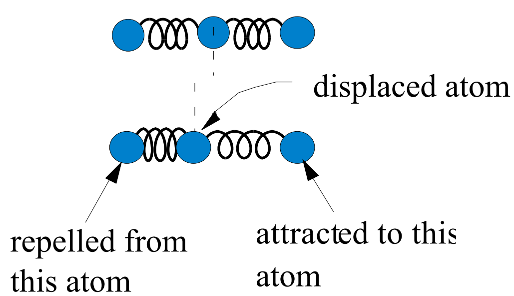

Figure 1.10 Forces on a displaced atom

The springs define the natural spacing of atoms, as shown in the top row of Figure 1.10. At this natural separation, there are no forces acting on the atoms. When the central atom is moved to the left (e.g., by a person exerting an external force), keeping the atoms on either side fixed at their natural positions, as shown in the lower portion of the figure, the spring on the left compresses and the spring on the right stretches. The stretched spring pulls the displaced atom to the right and the compressed spring pushes it to the right, in agreement with the effects of the electromagnetic forces between atomic electron clouds described earlier.

A model for solid materials, constructed using these components, accurately reflects the behavior of the solid when it is stretched or compressed. Of course, the atoms in the interior of a solid will have neighboring atoms on all sides. The type of atom and the process of formation of the solid, define the natural spacing throughout the object.

A particularly simple solid has the natural locations of its atoms in a rectangular pattern, as shown in Figure 1.11. Shown on the left of the figure are magnifications of a small region on the surface of a solid bar in the three states shown on the right.

The top (Compressed) state with external forces (arrows pointing inward) squeezing the bar, middle (Natural Length) state with no external forces affecting the bar, and bottom (Stretched) state with external forces pulling outward and stretching the bar.

The atoms in the Natural Length bar are in their natural and equilibrium locations. The springs have their natural length, and apply no forces to the atoms.

In the top bar compressed by external forces, the length is decreased and the atoms move to a new equilibrium separation closer to each other along the length. "Compression" forces (modeled by the compressed springs) are generated between the atoms that attempt to push the atoms back toward their natural spacing. If the object is squeezed harder the compression forces will resist, but can't prevent a further decrease in the length.

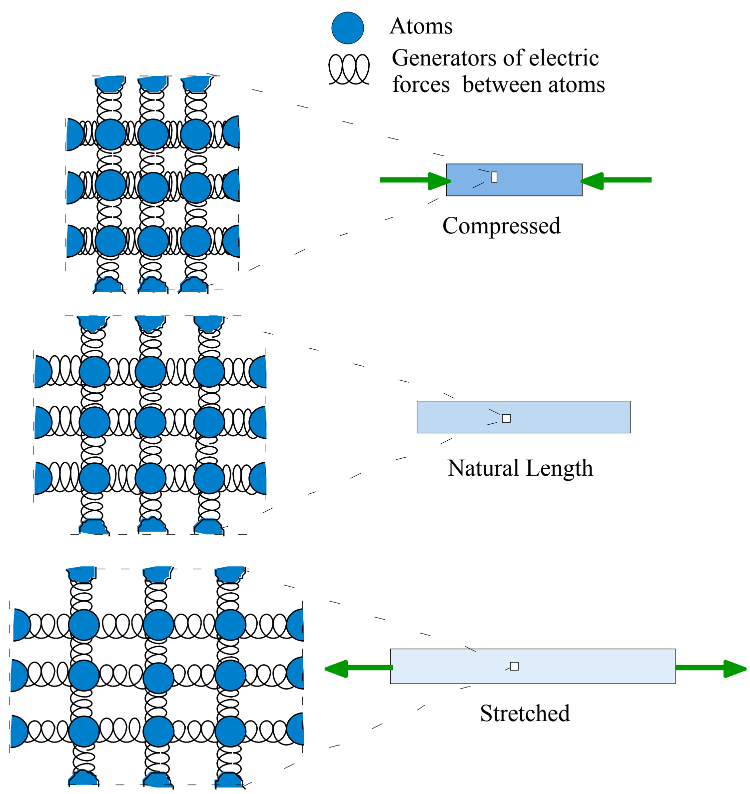

Figure 1.11 Functional model for the structure of solid matter.

When the bar is stretched, as shown in the bottom picture of Figure 1.11, the length increases, and the atoms move farther apart along the length of the object to new equilibrium separations. At the same time, between atoms, attractive "tension" forces (modeled by stretched springs) attempt to pull the atoms back toward their natural spacing. The tension forces will resist, but can't prevent, a further increase in the length.

The internal forces of tension and compression are called “elastic” if the object returns to its original length when the applied forces are removed. In the next few chapters only the elastic forces, tension and compression, will concern us.

A more detailed model is unnecessary. The simple model given above, using common springs to model the microscopic forces between atoms, provides a good description of the macroscopic forces generated by an elastically deformed object. The behavior of a spring is very familiar to us, and this familiarity will be used to develop confidence in a quantitative description of forces and related quantities before tackling the effects of gravity, a much less intuitive force.

Review of Scientific Notation

(1) Powers of Ten:

$$0.01 = 10^{-2}$$
$$0.1 = 10^{-1}$$
$$1 = 10^{0}$$
$$10 = 10^{1}$$
$$100 = 10^{2}$$
$$200 = 2\times 100 = 2\times 10^{2}$$
$$314159 = 3.14159\times 10^{5}$$
$$\frac{1}{100} = \frac{1}{10^{2}} = 10^{-2} = 0.01$$

(2) Multiplying and dividing:

$$\frac{1}{10^{-n}} = 10^{n}$$
$$10^{m}10^{n} = 10^{m+n}$$
$$\frac{10^{m}}{10^{n}} = (10^{m})(10^{-n}) = 10^{m-n}$$

Chapter Summary:

- Only four fundamental forces are known: gravitational, electromagnetic, weak nuclear and strong nuclear forces.
- Unification of electric and magnetic phenomena was accomplished when light was found to have properties of an electromagnetic wave, or of particles called photons. Electric or magnetic forces are an expression of the more general electromagnetic force.
- A force is electromagnetic in origin if gravity or nuclear forces are eliminated as candidates. All chemical reactions and phase changes are due to the electromagnetic forces between atoms.
- In an atomic nucleus, the *weak nuclear force* can cause a radioactive beta decay, which is always accompanied by the emission of a neutrino. In an atomic nucleus, nuclear particles (protons, neutrons) interact through the *strong nuclear force.*
- Objects with electric charge experience electric forces; attractive for charges of opposite signs and repulsive for charges with the same sign. Two neutral objects are charged by removing electrons from one object, that leaves it with a positive charge, and depositing those electrons on the other object, giving it a negative charge.
- In a neutral atom, positively charged protons reside in the nucleus (size 10^{-14} m), with a surrounding cloud (size 10^{-10} m) containing an equal number of negatively charged electrons. Forces between neutral atoms are determined by the interaction of their electron clouds.
- In an undistorted object, the atoms locate at natural separations where electromagnetic forces acting on each atom are absent (none, zero).
- For an atom shifted in location relative to its neighbors, electromagnetic forces act in a direction to restore the atom to its original location. For the atoms in an undistorted object, the natural and equilibrium positions are the same.
- In a stretched or compressed object, atoms find a new equilibrium separation, where balanced electromagnetic forces (non-zero) act on each atom. These internal forces are called tension forces when generated by stretching, and compression forces when generated by squeezing.
- A distortion is “elastic” if a *solid* object quickly returns to its original length when the applied stretching or compressing forces are removed.