1 Understanding Macroscopic Systems

The inanimate objects or living organisms encountered in everyday life are all much larger than atomic size. They have many important properties which we would like to understand and exploit for practical purposes. How can this be done? In particular, can our knowledge of the atomic structure of matter be used to achieve such a useful understanding? The present chapter begins to explore these questions which will be addressed throughout the rest of the book.

A. Macroscopic systems and atomic knowledge

Macroscopic systems

In everyday life we deal with many different kinds of systems, e.g., with solid objects like metal coins or automobiles, with liquids like water, with gases like air, and with living organisms like animals or people. All these diverse systems are *macroscopic*, i.e., they are much larger than atomic size. Indeed, the size of a atom is about 10^{-10} meter. Thus even a barely visible speck of dust, 0.1 mm in size, is about a million times larger than an atom.

The word macroscopic means large-scale, as contrasted with the word microscopic which means small-scale (i.e., of atomic size). Since these words are so similar that they can easily be confused, we shall avoid use of the word microscopic.

Properties of macroscopic systems. To deal with all these macroscopic systems, we need to understand their commonly observed properties sufficiently well to explain or predict how these systems behave under various circumstances. For example, we might want to understand how the temperatures of objects change when they are heated or cooled, why drilling a metal makes it hot, why solids melt to form liquids, etc..

How can such an understanding be achieved?

Application of atomic knowledge

We know that all matter consists ultimately of various atoms. Since a macroscopic system is much larger than atomic size, any such system consists thus of a very large number of atoms (or of molecules consisting of such atoms).

Typical number of atoms in a macroscopic system. For example, consider a cubical block of copper 1 cm (i.e., 10^{-2} m) on each side so that its volume is $(10^{-2}\text{m})^3 = 10^{-6}\ \text{m}^3$. By contrast, the volume occupiedby a single copper atom, which is about 10^{-10} m in size, is about $(10^{-10}\ \text{m})^3 = 10^{-30}\ \text{m}^3$. ~~Thus the number of copper atoms in this block is about $(10^{-6}\ \text{m}^3)/(10^{-30}\ \text{m}^3) =$~~

10^{24}. This is indeed a very large number of atoms, typical of the number of atoms contained in an everyday macroscopic system.

Applying atomic knowledge to macroscopic systems. We have some knowledge about atomic particles, e.g., some mechanics knowledge about the motion and interactions of such particles. The knowledge that any macroscopic system consists of many such particles should thus, in principle, allow us to infer some important properties of macroscopic system. Is this actually possible in practice?

At first blush, the task of applying atomic knowledge to such a vast number of atomic particles appears impossibly complex. However, the task is actually fairly easy for the following reasons:

(a) Some important general properties of macroscopic systems depend only on some general properties of atomic particles, but not on many of their detailed properties. Thus one can make significant progress without getting involved in complex arguments.

Indeed, one can even make substantial progress without a knowledge of quantum mechanics which is ultimately required for a more accurate understanding of atomic particles.

(b) The very fact that the number of atomic particles is so extremely large is a help rather than a hindrance because it allows one to apply statistics (i.e., probability considerations) with great effectiveness.

> For example, it is impossible to predict when a particular individual person will die or will win in a roulette game. But very reliable statistical predictions can be made about *large numbers* of individuals. (This is why insurance companies and gambling casinos are very successful enterprises.) Even more reliable statistical predictions can, therefore, be made about macroscopic systems since they involve such extremely large numbers of atomic particles.

Central problem

The preceding comments indicate that we need to address the following central problem:

> How can one understand the properties of macroscopic systems by exploiting available knowledge about their constituent atomic particles?

Overview of the book. The rest of the book will deal with this problem by doing the following:

(a) It will exploit basic knowledge about the mechanics of particles to infer some important general properties of macroscopic systems which consist of very many atomic particles.

(b) It will focus special attention on the properties of macroscopic systems in situations that don't change with time, i.e., in so-called "equilibrium situations". (Such situations are particularly simple and important since they occur quite commonly.)

(c) It will also examine qualitatively how macroscopic systems change to attain such equilibrium situations.

(d) However, it will *not* deal quantitatively with most time-dependent processes (e.g., it will not examine *how rapidly* systems change to attain equilibrium situations). Such time-dependent processes are sufficiently complex that they are best studied in more advanced courses.

Problems

[A-1] ***Very large numbers***

Suppose that you wanted to count some large number of objects and that, starting from 1, you counted at the rate of one number per second. To appreciate the size of some large numbers, estimate how many years you would require to count the following:

(a) The number of people on the earth (i.e., about 10 billion)? Compare the required counting time with a human lifetime (about 75 years).

(b) The number of atoms in a cube of copper 1 cm on a side (i.e., about 10^{24} atoms). Compare the required counting time with the estimated age of the universe (about 10^{10} years). <*a-3*>

B. Atomic and macroscopic descriptions

State of a system. The *state* of a system is a sufficiently complete specification of the system that all its relevant properties are thereby specified. The state of a system can, accordingely, be specified by the values of a sufficiently large number of quantities describing the system.

Consider any macroscopic system (e.g., the helium gas in the container shown in Fig. B-1, or a copper block, or any other such system). How many quantities are needed to describe the state of such a macroscopic system? As the following comments indicate, the answer to this question depends crucially on whether on wishes to describe the system from an atomic point of view or from a macroscopic point of view.

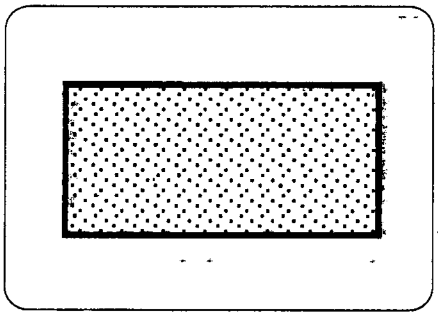

Fig. B-1. Helium gas inside a container. (The atoms of the gas move randomly throughout this container.)

Atomic description

Suppose that one considers a macroscopic system from an atomiic point of view which considers all the atomic particles in the system system. Then the state of the system can be specified by specifying the position and the velocity of *every atomic particle* in the system.

> This is a complete description since all the other mechanical properties of the system (e.g., its energy and momentum) would then also be specified. According to Newtonian mechanics, knowledge of these positions and velocities at any one time would (in principle) also allow one to predict the positions and velocities the particles at any other time.

Specification of a basic state. How many quantities are then required to specify a *basic state* of the system (i.e., a state described from the preceding atomic point of view)? If there are N atoms in the system, one must then specify N positions and N velocities (and each of these is a vector quantity specified by 3 components since the particles are located in three-dimensional space). Since there are typically something like 10^{24} atomic particles in a macroscopic system, the number of quantities which need to be specified is thus enormously large!

Such a basic state is also called a microscopic state.

If atomic motions are described more accurately by quantum mechanics rather than by Newtonian mechanics, the basic state of a system is a *quantum state* of this system. But the number of quantities needed for the complete specification of such a state is similarly large.

Macroscopic description

The preceding atomic description of a macroscopic system is, of course, enormously complex and quite different from the ways used to describe macroscopic systems in everyday life.

Equilibrium situations

Consider the simple situation where a macroscopic system is in *equilibrium*, i.e., that it is at rest (relative to the surface of the earth or some other inertial frame) and that its macroscopic properties don't change in the course of time.

For example, the system might be a copper block lying on a table. Or, as illustrated in Fig. B-1, it might be some helium gas which has been left sitting in the container illustrated in Fig. A-1. In all these cases, the individual atoms in the system move about. (Thus the atoms in the copper block vibrate slightly back and forth about their normal positions in the solid. Similarly, the molecules of the gas move randomly throughout the entire container.) However, the visible macroscopic properties of the system remain unchanged.

A molecule of helium consists of a single helium atom. Other molecules may consist of several atoms. For example, a molecule of nitrogen gas consists of two nitrogen atoms.

Quantities describing the macroscopic state of a gas. The macroscopic state of a system can be described by a few quantities measurable by large-scale observations that don't pay attention to individual atoms. For example, the following are some typical quantities which can be used to describe the macroscopic state of a gas in equilibrium (e.g., the gas in Fig. B-1).

(a) The *volume* of the gas (i.e., the volume throughout which all the gas molecules can move).

(b) The *pressure* of the gas, i.e., the magnitude of the force per unit area on any surface in contact with the gas. (In equilibrium, this pressure is the same at any point in the gas.)

(c) The *temperature* of the gas. This temperature might be measured by the characteristic of any thermometer in contact with the gas (e.g., by the length of the column of mercury in a mercury-in-glass thermometer, or by the number indicated by the pointer of a dial thermometer).

(d) The total *internal energy* of the gas (i.e., the total energy of all the molecules in the gas).

The next chapter will discuss how this total internal energy can be determined by large-scale measurements.

Actually, it is found that any two such quantities are sufficient to determine completely the macroscopic state of a gas in equilibrium. For example, if the volume and pressure of the gas are known, some definite coorresponding temperature will be indicated on the measuring thermometer and some definite corresponding internal energy will be possessed by the gas. Similarly, if the volume and temperature of the gas is known, the gas will have someo definite corresponding pressure and internal energy.

Specification of the equilibrium macrostate of a system. The macroscopic state of a system can be more briefly called its *macrostate*. The preceding comments thus indicate that the macrostate of any macroscopic system in equilibrium can be specified by the values of very few quantities (e.g., of two such quantities in the case of a gas).

Time-varying situations

Example of a time-varying process. Time-varying situations are more complex than equilibrium situations. For example, consider the helium gas initially in equilibirum in the left half of the container shown in Fig. B-2. If the partition dividing this container in two halves is suddently removed, some of the gas starts moving into the initially empty right half of the container. During this process, the gas is no longer in equilibrium, nor is the pressure the same at all points of the gas. However, as schematically indicated in Fig. B-2, after some time the gas will again come to equilibrium in a different macrostate where the gas is now uniformly distributed throughout both halves of the container.

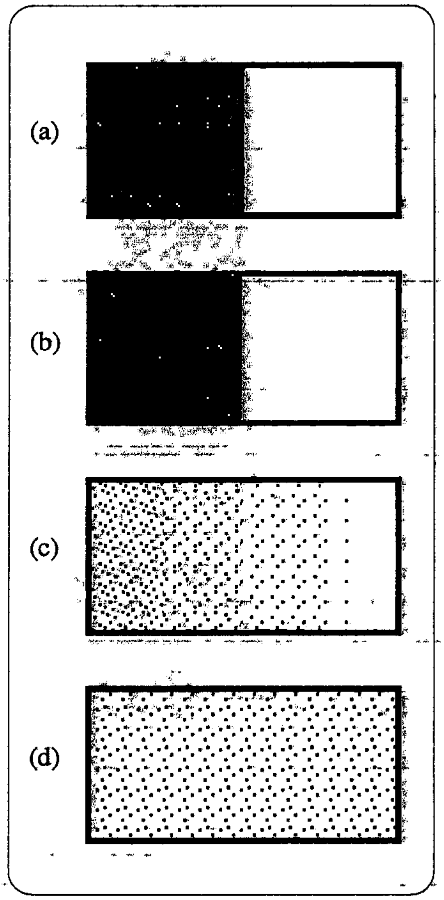

Fig. B-2. Schematic illustration of a time-varying process. (a) Gas initially in equilibrium in left half of a container. (b) Situation immediately after dividing partition is removed. (c) Situation a short time thereafter. (d) Final equilibrium situation.

Specification of a non-equilibrium macrostate. Suppose that a macroscopic system is not in equilibrium. Its state at any instant can then be specified by describing each small part of the system, where eqfocusing on small regions of the system each of which is still much larger than atomic size, but

Specification of a non-equilibrium macrostate. If a macroscopic system is not in equilibrium, its state at any instant can be specified by describing each small part of the system (where each such part is much smaller than the entire system, but still very much larger than atomic size). For example, when weather forecasters describe the state of the atmosphere at some time, they specify the temperature and pressure of various small regions of the atmosphere (where these temperatures and pressures are usually not quite the same in different regions).

The number of quantities needed for the specification of a non-equilibrium situation is thus appreciably larger than for an equilibrium situation. However, it is still enormously much less than would be required for an atomic description of the system.

Relation between macrostates and basic states

As we have seen, the macroscopic state of a system can be described by a rather few quantities, especially when the system is in equilibrium. However, the mere knowledge that a macroscopic system is in such a state provides very little information about the positions or velocities of all the individual atoms in the system. Indeed, the system can then be in any one of an enormously large number of basis states described from an atomic point of view.

All the rest of the book will then be concerned with understanding the relation between the macroscopic and atomic descriptions -- so that basic atomic knowledge can provide us with useful insights about the properties of macroscopic systems.

Problems

[B-1] ***Pressure and forces in a fluid***

The molecules of a fluid (gas or liquid) exert, on any small surface immersed at any point of the fluid, a force perpendicular to this surface and directed away from the fluid. (See Fig. B-3.) The magnitude F of this force is proportional to the area A of the surface (i.e., proportional to the number of molecules adjacent to this surface). The pressure p of the fluid at this point is defined as the magnitude of the force per unit area, i..e., as the ratio

$$p = \frac{F}{A} . \qquad \text{(B-1)}$$

(The pressure does not depend on the orientation of the surface, e.g., on whether it is horizontal or vertical.) If the fluid is in equilibrium, the pressure must be the same at every point in the fluid since any pressure difference would cause the fluid to move.

The gas illustrated in Fig. B-3 is in eqilibrium and the pressure at any point of it is 2.0×10^5 N/m^2 (where N is the standard abbreviation for newton and m is the abbreviation for meter). The botttom of the container enclosing this gas has an area of 0.046 m^2 and the right side of the container has an area of 0.030 m^2.

(a) What is the force (magnitude and direction) of the force exerted by the gas on the bottom of the container?

(b) What is the force (magnitude and direction) of the force exerted by the gas on the right side of the container? <a-1>

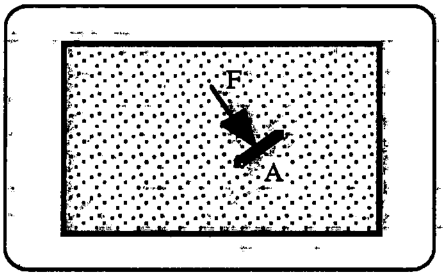

Fig. B-3. Force exerted on a small surface of an object immersed in a gas.
The unit N/m^2 is also called *pascal* (abbreviated as *Pa*).

[B-2] ***Force exerted by atmospheric pressure***

The pressure exerted at sea level by the air in the atmosphere is about 1 bar (where bar = 10^5 N/m^2 is a covenenient unit of barometric pressure).

(a) The circular top of a can of juice has a radius of 5.0 cm. What is the magnitude F of the force exerted on the top of this can by the air in the atmosphere?

(b) What is the ratio F/w of this force compared to the weight w of a man having a mass of 80 kg?

(c) Why does the can not collapse despite the force exerted on it by the air in the atmosphere? <a-4>

[B-3] ***Work done by pressure***

Fig. B-4 shows a gas inside a cylinder closed by a movable piston of area A. The gas, in equilibrium at a pressure p, then exerts on the piston a force pA to the right. To maintain the piston at rest, a person applies to the piston an opposing force F = pA to the left.

Suppose that the applied force on the piston is reduced very slightly so that the piston moves very slowly to the right by a very small distance s. During this time, the gas remains very nearly in equilibrium at a pressure essentially equal to p.

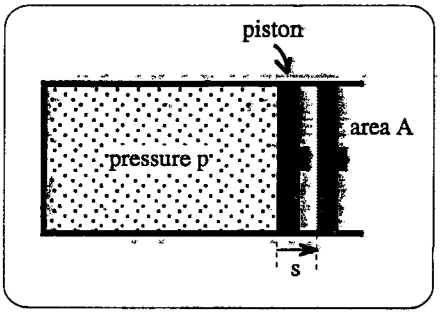

Fig. B-4. Gas in a cylinder closed by a movable piston.

(a) What then is the work done on the gas by the applied force F? (Express your answer in terms of p, A, and s.) Is this work positive or negative?
(b) When the piston moves, the volume V of the gas changes by a small amount dV. What is this change of volume? (Express your answer in terms of A and s.) Is this change positive or negative (i.e., does the volume of the gas increase or decrease when the piston moves to the right)?
(c) Express the work done on the gas by the applied force F solely in terms of the pressure p and the volume change dV.
(d) In the preceding situation the piston was moved to the right to that the gas was allowed to expand. Suppose, instead, that the piston is moved slowly to the left so as to compress the gas (i.e., so as to reduce its volume). Would the change dV of the volume of the gas then be positive or negative? Would the work done on the gas by the applied force then be positive or negative? *<a-5>*

[B-4] ***Pressure change with volume***

The gas in Fig. B-4 exerts a pressure on the piston because the moving gas molecules near the piston continually collide with it and thus exert a net force on it.

Suppose that the piston in Fig. B-4 is slowly moved to the right by a considerable distance while the gas remains at room temperature. The volume of the gas then increases appreciably while the speeds of the gas molecules remain unchanged.

(a) Does the number of gas molecules in a region near the piston then increase, decrease, or remain the same?
(b) During any time interval, does the number of collisions of gas molecules with the piston then increase, decrease, or remain the same? Correspondingly, does the pressure exerted by the gas on the piston then increase, decrease, or remain the same? *<a-2>*

C. Summary

Definitions

Macroscopic: Large-scale (i.e., much larger than atomic size).

Macroscopic system: A system much larger than atomic size (and thus consisting of very many atoms).

Macroscopic state (or macrostate) of a system: The state of a system specified from a large-scale point of view unconcerned with the individual atoms in the systems.

Basic state of a system: The state of a system specified from an atomic point of view which considers all the individual atoms in the system.

Equilibrium state. A macrostate which remains unchanged with time.

Important knowledge

Relation between macroscopic and atomic descriptions. The macrostate of a system is specified by very few quantities (especially when the system is in equilibrium). By contrast, the basic state of a system is specified by an enormously large number of quantities (e.g., the positions and velocities of all the atoms in the system).