PRESSURE

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Phases of matter. The three most common phases of matter that are constantly around us are solid, liquid and gas. Let us discuss their properties in a bit more detail.

Gas. The most familiar gas is air. Gases are quite similar in their properties so we can think about air when thinking about properties of some gas. A gas does not have a particular shape. For example if you take an empty bottle (really empty, even without air) and fill it with gas, the gas will take the shape of the bottle. Even more than that, gas will spread out in the whole volume of the bottle, even if initially it was contained in a much smaller volume. If instead of the bottle you fill a room with the same amount of gas, it will still take up the whole volume. So gas easily changes shape and volume.

Why does gas behave like this? Remember that everything around us is built out of tiny atoms and molecules and gases are no different. In a gas atoms or molecules are quite far from each other and they almost don't interact with each other. They just fly all over the place and occasionally collide with each other or the walls of the container. It is then easy to understand why gases take up the whole volume provided to them. Atoms or molecules of gas will fly somewhere until they reach a wall, which means taking up the whole space.

Liquid. We are all familiar with liquid water and a bunch of other liquids, such as vegetable oil, gasoline, etc. On one hand liquids are similar to gases: they could also take the shape of any bottle you pour them into. But on the other hand if you pour half a gallon of water into a gallon jug the water will not fill the jug completely. So liquids have particular volume (which is really hard to change) but easily change shape.

This behavior could also be described from the point of view of atoms and molecules. They have a property that they attract each other when they are not directly in contact. What if they are located closer to each other and interact stronger than in a gas? Now they don't want to move too far from each other and instead of just flying around individually atoms and molecules tend to stay together. This explains why liquid has a particular volume. But atoms and molecules still move around each other, they just don't go too far. This explains why shape of the liquid is variable.

Solid. Most of the objects we interact with are solid: a table, a car, a laptop. Their most characteristic property is that they have a certain shape and volume. If you put a piece of metal into a bottle, nothing would happen to its shape or volume.

In solid objects atoms and molecules are interacting even stronger than in liquids. As a result, they are forced to stay in a particular place. The most illuminating example of a solid is a crystal. In a crystal atoms are placed in a regular lattice and can't move to other places. Because of this crystal has a particular shape. You may ask: what about kinetic energy of the atoms? Since temperature is a measure of average internal kinetic energy and we know that solids have temperature, how can atoms not move? The answer is that they move, but just a little. They oscillate about their equilibrium positions and cannot get far from these positions.

Properties of gases. Our future discussion will concern thermal properties of gases. You may think: why is it important at all? The answer is, thermal properties of gases are important in many cases. For instance, gases produced from burning fuel set parts of a car engine to motion and, in fact, are responsible for moving the car forward. A more global example is the Earth's atmosphere with processes in it responsible for weather and climate. It's very important to understand these processes.

Consider a gas in some container. By which physical properties can we characterize the gas? Some of the familiar properties that we already discussed are temperature T and volume V (which is the same as volume of the container). But there is one more property which we will discuss today: pressure. Among others one could name mass and chemical composition (will be discussed later).

Pressure. From daily life we know that in some situations not just the force matters but also to which area this force is applied. Previously we did not discuss where exactly is a force applied, but in fact it never could be in just a point - there should be some area. When a person stands on the floor, the normal force which the floor exerts on the person is applied throughout the whole area of their feet. It is thus important to consider pressure (denoted by p), which is defined as a ratio of force F to the area A to which this force is applied:

$$p = \frac{F}{A}$$

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Units of pressure are $\mathrm{N/m^2}$ and have a special name: Pascals, or Pa. For example, let's calculate the pressure a person exerts on the floor when standing on two feet. Let us say for simplicity that each of the feet is a rectangle with sides 30 cm $\times$ 10 cm and mass of the person is 60 kg. Then pressure is

$$p = \frac{F}{A} = \frac{mg}{A} = \frac{60 \cdot 10\ \mathrm{N}}{2 \cdot 10 \cdot 30\ \mathrm{cm}^2} = \frac{600}{0.06}\frac{\mathrm{N}}{\mathrm{m}^2} = 10000\ \mathrm{Pa} = 10\ \mathrm{kPa}$$

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Normally we do not care too much about this pressure. However if we try to walk on snow it becomes important: if the pressure is too big, our feet will fall through the snow. In order to reduce pressure and prevent falling through the snow one could make the area of contact bigger by wearing snowshoes or skis.

Pressure in gases. How is it all related to gases? Gases exert pressure on the container walls. It is quite easy to understand from the microscopic picture of a gas. Remember that a gas consists of molecules flying around randomly and colliding with each other and the walls of the container. When a molecule hits a wall, its' momentum is changed which means the wall acted on it with some force. By Newton's third law it means that the molecule acted on the wall with some force. There is an enormous amount of molecules hitting the wall every second so the average force is very close to a constant and depends just on the area of the wall we are considering. Therefore, gas is characterized by its' pressure. The force with which the gas presses the wall is always directed perpendicularly to this wall and outwards from the container.

One example of pressure in a gas is atmospheric pressure. Our atmosphere acts upon every object with a pressure. At sea level it is normally about 100 kPa - so, on every square meter it acts with 100000 Newtons. How big is the atmospheric pressure? To appreciate its scale let's calculate the force with which atmosphere pushes down on the top surface of a desk. Let's say the desk has a rectangular shape, 1 meter by 2 meters. Since pressure is force divided by area, to find force we need to multiply pressure by area:

$$F = pA = 100000\ \mathrm{Pa} \cdot 2\ \mathrm{m}^2 = 200000\ \mathrm{N}$$

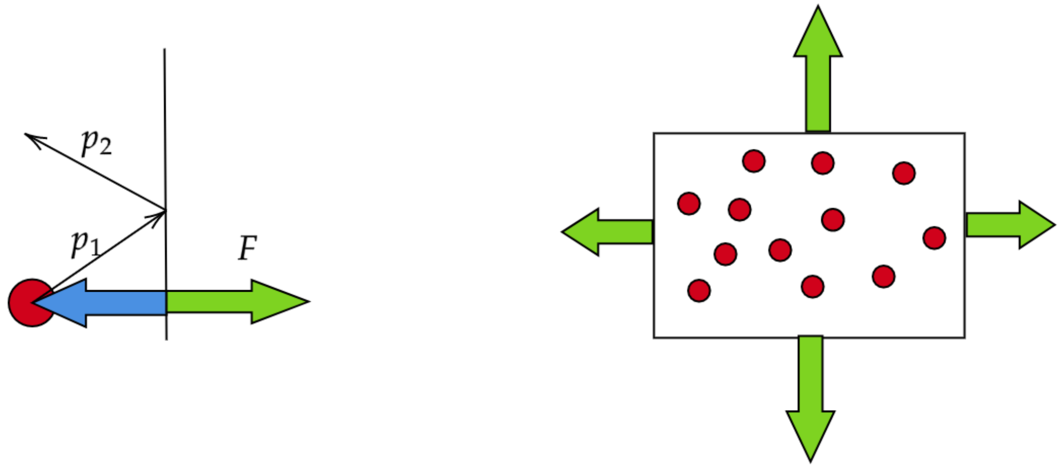

FIGURE 1. **Left figure:** if a molecule (red ball) collides with a container wall, molecule's momentum is changed from p_1 to p_2. Therefore wall acted on it with some force (shown in blue) and by Newton's third law the molecules acts on the wall with an equal force F (shown in green). **Right figure:** Force of pressure acting on a container wall is directed outwards on each wall. Note that magnitude of the force is larger for walls with bigger area: if pressure is the same, force grows with area.

How large is the force of 200000 N? Let's compare it to weight of something. An object with mass m has weight mg, so mass of the object with weight 200000 N is

$$m = \frac{200000 \text{ N}}{g} = \frac{200000}{10} \text{ kg} = 20000 \text{ kg}$$

This is a mass of 4 elephants! So the force atmospheric pressures acting on the top surface of the desk is the same as if we put there four elephants. However, the atmosphere does not break the desk because it not only presses on the surface from above, but it also presses on the bottom surface of the desk from below with exactly the same force (because pressure and area are the same). As a result the desk does not break, just squeezes a little.

HOMEWORK

1. In what states are the following substances at room temperature: water, sugar, air, tin, alcohol, ice, oxygen, aluminum, milk, nitrogen? Make your answer in a form of a table with three columns corresponding to three basic states of matter.

2. A 45 kg skier has his ski on. The length of each ski is 1.5 m; the width is 10 cm. Find pressure that the skier is applying to the snow.

3. What pressure you produce when you are pushing a pushpin into a wall with a force of 50 N? Take the area of the pushpin tip as 0.01 mm^2. How does this pressure compare to the atmospheric pressure?

4. A fish tank 60 cm long, 40 cm wide and 30 cm high is full of water. Calculate pressure produced by the fish tank to the surface of the table. Water has density 1000 kg/m^3.

***5.** Estimate the mass of Earth's atmosphere. You are given atmospheric pressure $p_0 =$ 100000 Pa and radius of the Earth $R = 6400$ km. *Hint: surface area of a sphere of radius R is $4\pi R^2$.*