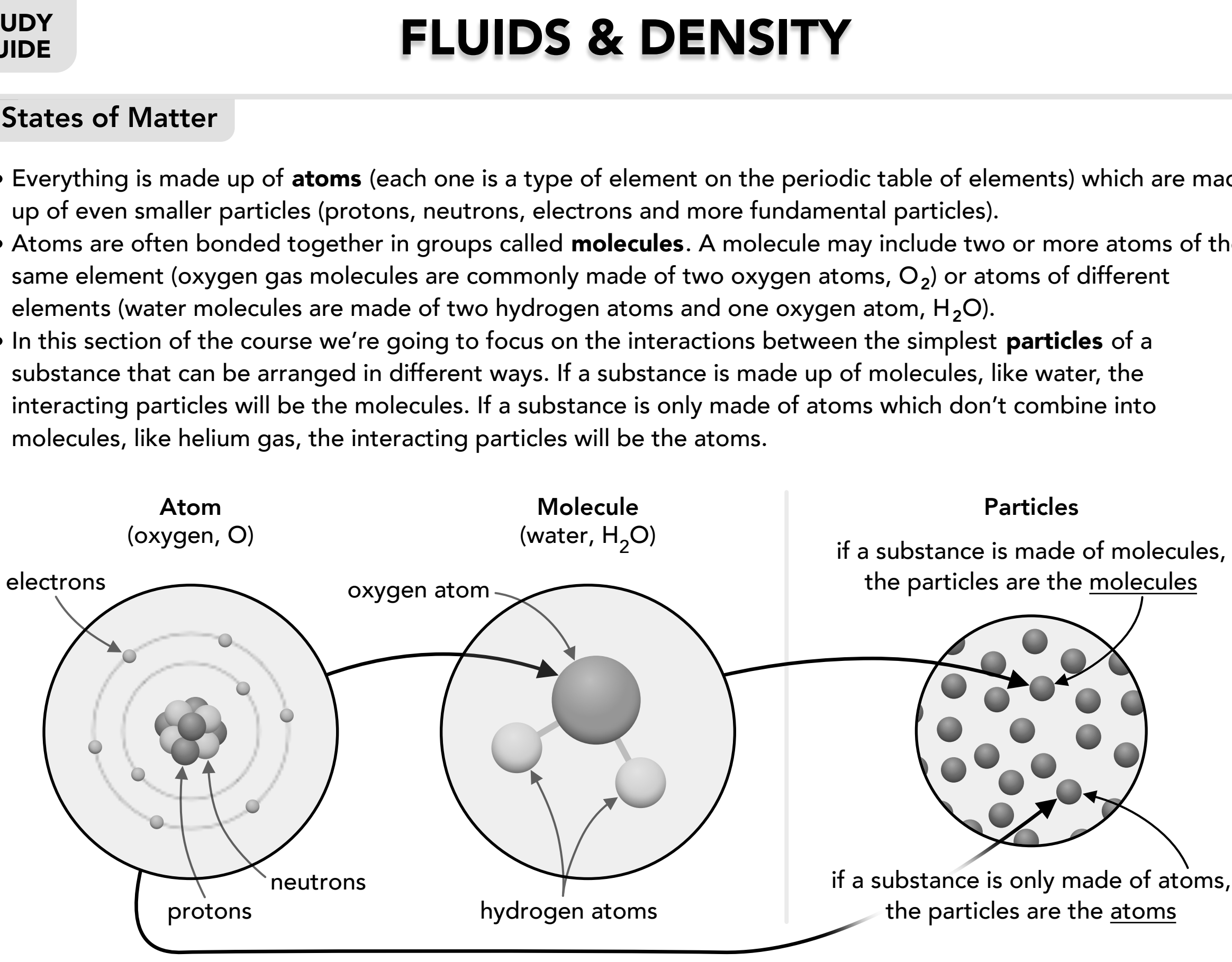
STUDY GUIDE

FLUIDS & DENSITY

States of Matter

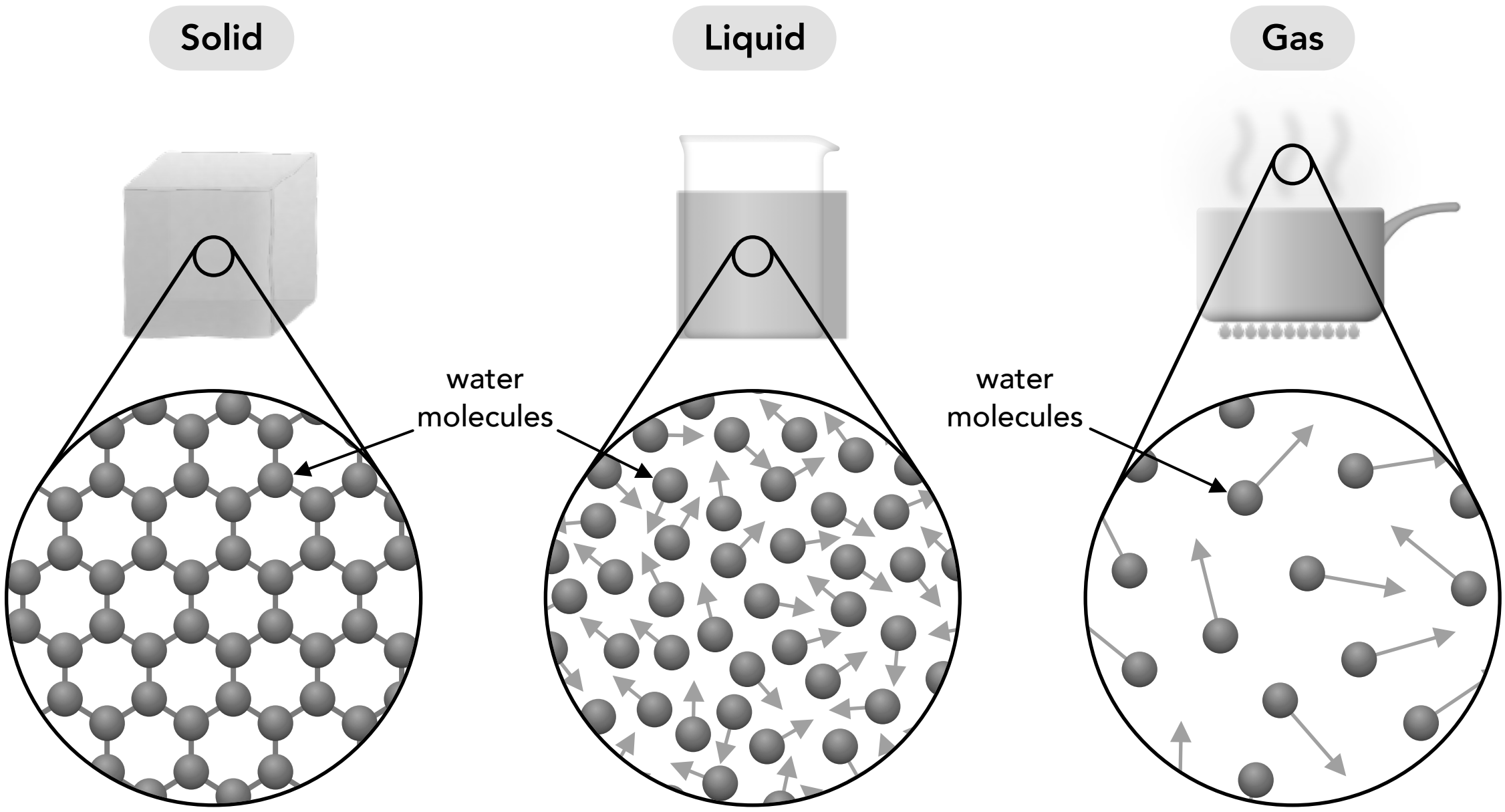
- Everything is made up of **atoms** (each one is a type of element on the periodic table of elements) which are made up of even smaller particles (protons, neutrons, electrons and more fundamental particles).
- Atoms are often bonded together in groups called **molecules**. A molecule may include two or more atoms of the same element (oxygen gas molecules are commonly made of two oxygen atoms, O_2) or atoms of different elements (water molecules are made of two hydrogen atoms and one oxygen atom, H_2O).
- In this section of the course we're going to focus on the interactions between the simplest **particles** of a substance that can be arranged in different ways. If a substance is made up of molecules, like water, the interacting particles will be the molecules. If a substance is only made of atoms which don't combine into molecules, like helium gas, the interacting particles will be the atoms.



- There are 4 states of matter (4 forms that matter can exist in): solid, liquid, gas and plasma. The difference between these states is the arrangement and interaction of the particles (atoms or molecules) that make up the substance, which depends on the kinetic energy of the particles (the temperature of the substance). Plasma is a little more complicated and won't be covered in this course.
- When matter is in a **solid** state the particles are tightly packed and strongly bonded together in an organized rigid structure. The substance is at a lower temperature than the other states of matter. The particles can vibrate and move slightly but they are constrained by the atomic or intermolecular bonds. Solids can be stretched or compressed slightly with enough force (see the section on springs and elasticity of materials) but the bonds keep the particles in the same structure.
- When matter is in a **liquid** state the particles are free to move around and the substance can **flow** because the motion (kinetic energy) of the particles prevents them from bonding together like they do in a solid. The particles are only slightly farther apart than they are in a solid but they have no organized structure. The substance is at a higher temperature than it is in its solid state and a lower temperature than it is in its gas state. Liquids have no fixed shape and will flow to take the shape of their container. Like a solid, a liquid is nearly incompressible.
- When matter is in a **gas** state the particles are even more free to move than in the liquid state and the substance can **flow** like a liquid. The substance is at a higher temperature than it is in its liquid state. The particles are moving very fast (they have a higher kinetic energy) and are much farther apart than in the solid or liquid state. Like a liquid, a gas has no fixed shape and takes the shape of its container. However, because the particles are far apart a gas is very compressible and its volume will easily change when a force is applied to it.

Lower temperature
(particles have less kinetic energy)

Higher temperature
(particles have more kinetic energy)



In the solid state, the molecules are bonded closely together in an organized rigid structure

In the liquid state, the molecules are free to move around and the liquid takes the shape of its container

In the gas state, the molecules are much farther apart, move much faster and fill their container

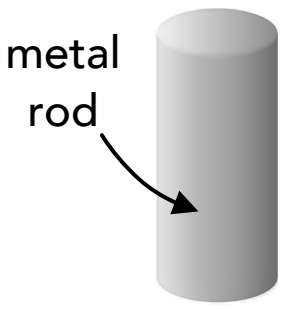
- Any substance can exist as a solid, liquid or gas depending on its temperature (the average kinetic energy of its particles). For example, water (H_2O) is a solid (ice) at temperatures below 0°C/32°F, a liquid at temperatures between 0°C/32°F and 100°C/212°F, and a gas (steam/water vapor) at temperatures above 100°C/212°F (these temperatures apply at normal atmospheric pressure).
- Heating a solid will turn it into a liquid (known as melting), heating a liquid will turn it into a gas (known as boiling), cooling a gas will turn it into a liquid (known as condensing) and cooling a liquid will turn it into a solid (known as freezing).
- It's also possible for matter to transition directly between a solid and a gas (known as sublimation and deposition). Dry ice (often used to keep items cold during shipping) is frozen carbon dioxide which is usually a gas at room temperature. The "smoke" or "fog" produced by dry ice is the carbon dioxide transitioning from a solid to a gas.

Fluids

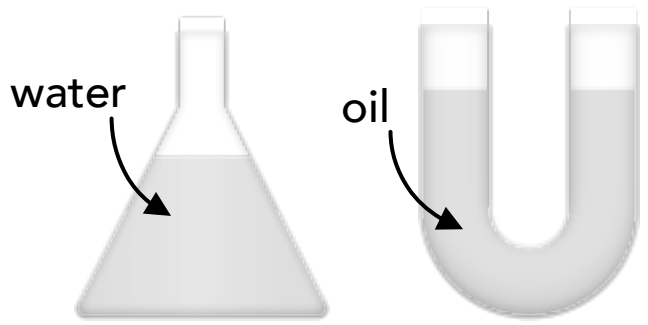
- A **fluid** is a substance (a liquid or gas) that can **flow** and has no fixed shape (it takes the shape of its container).
- Liquids and gasses are both fluids because their particles (atoms or molecules) can move freely relative to each other and there are no strong bonds between particles (although there are still some forces between particles).
- By contrast, a solid is not a fluid because its particles are strongly bonded together in an organized rigid structure. A solid has a fixed shape which can stretch a small amount when a force is applied to it, but it will not flow.
- A gas is **compressible** (it will change volume when compressed) but a liquid is considered to be **nearly incompressible** (it will barely change volume when compressed).
- The technical definition of a fluid is a material with zero shear modulus which will continue to deform when a shear force is applied to it. A fluid will flow continously rather than stretch to a fixed shape like a solid (but this is not required knowledge for this course).

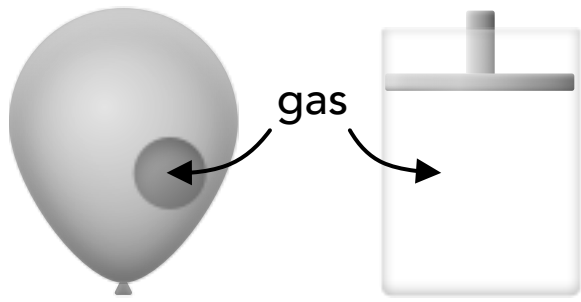
Fluids

Solid | **Liquid** | **Gas**

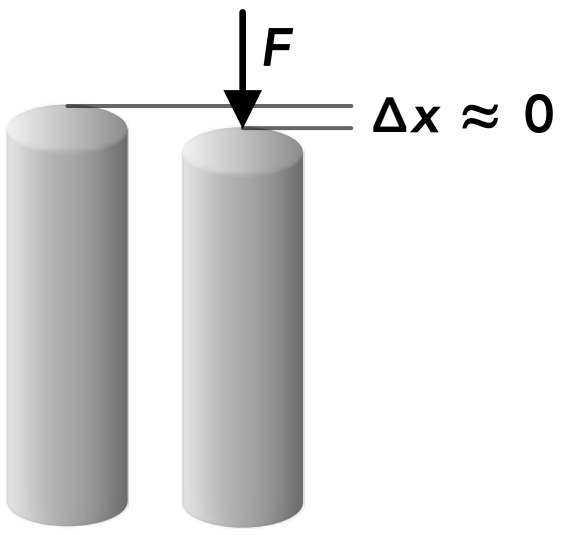


Solids have a fixed shape

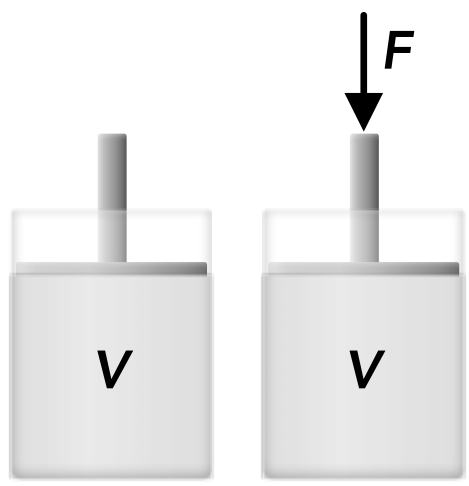




Fluids have no fixed shape, they take the shape of their container

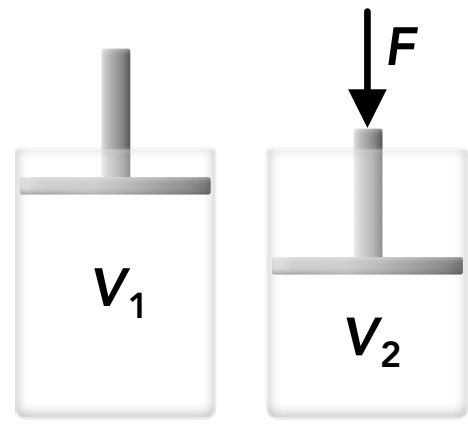


Solids are nearly incompressible



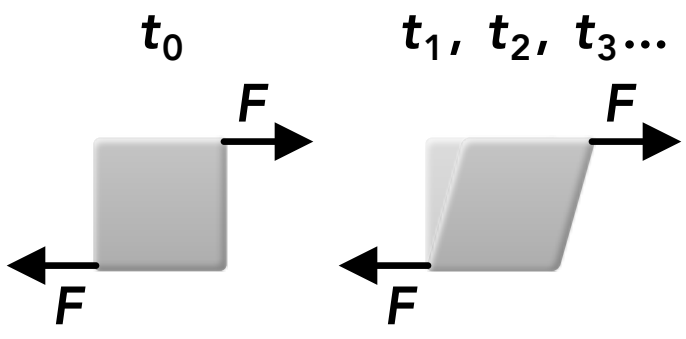
$\Delta V \approx 0$

Liquids are nearly incompressible

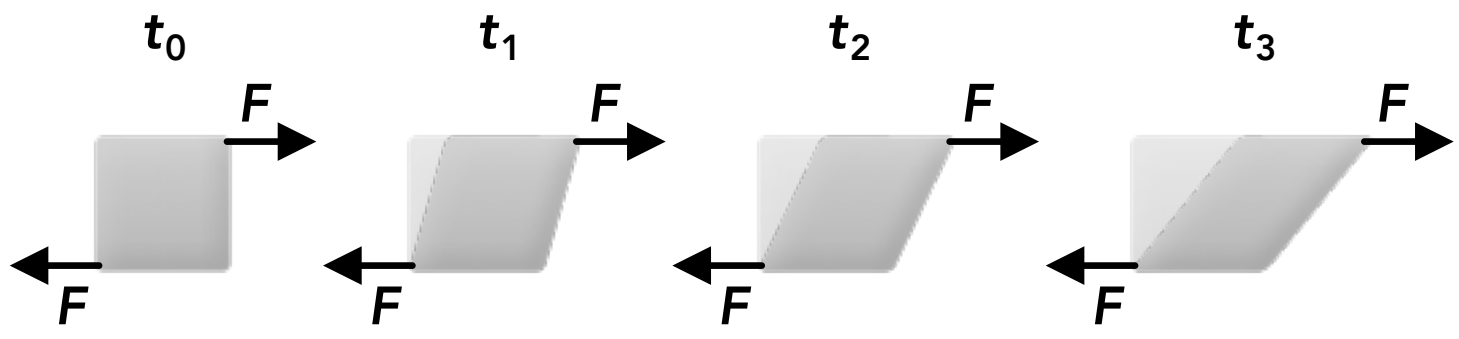


$V_1 > V_2$

Gasses are very compressible



Solids deform slightly when a shear force is applied



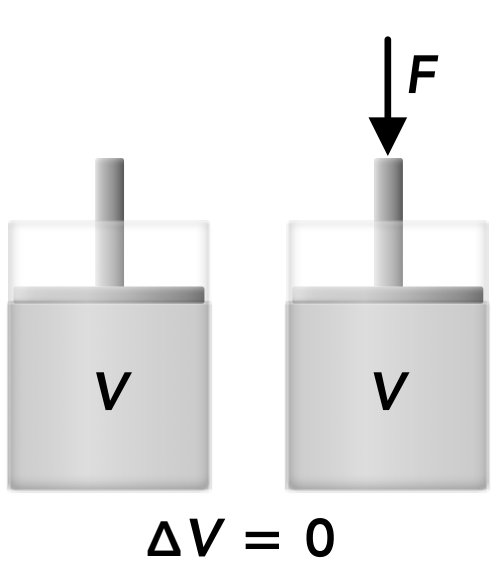
Fluids continue to deform or "flow" when a shear force is applied (not required knowledge for this course)

- When working with gasses, we're going to treat them as compressible and we will not be learning about the flow of gasses (the fact that they are compressible makes things more complicated).
- When working with liquids, we're going to treat them as "ideal fluids" (gasses cannot be considered ideal fluids).
- An **ideal fluid**:
  1. Is **completely incompressible**: its volume and density do not change when a force is applied to it, regardless of the pressure of the fluid. The particles in an ideal fluid do not get closer or farther apart.
  2. Has **no viscosity**: it does not resist flow and there is no friction between the fluid particles or between the particles and the container. (Viscosity is covered in another section).

Ideal fluids

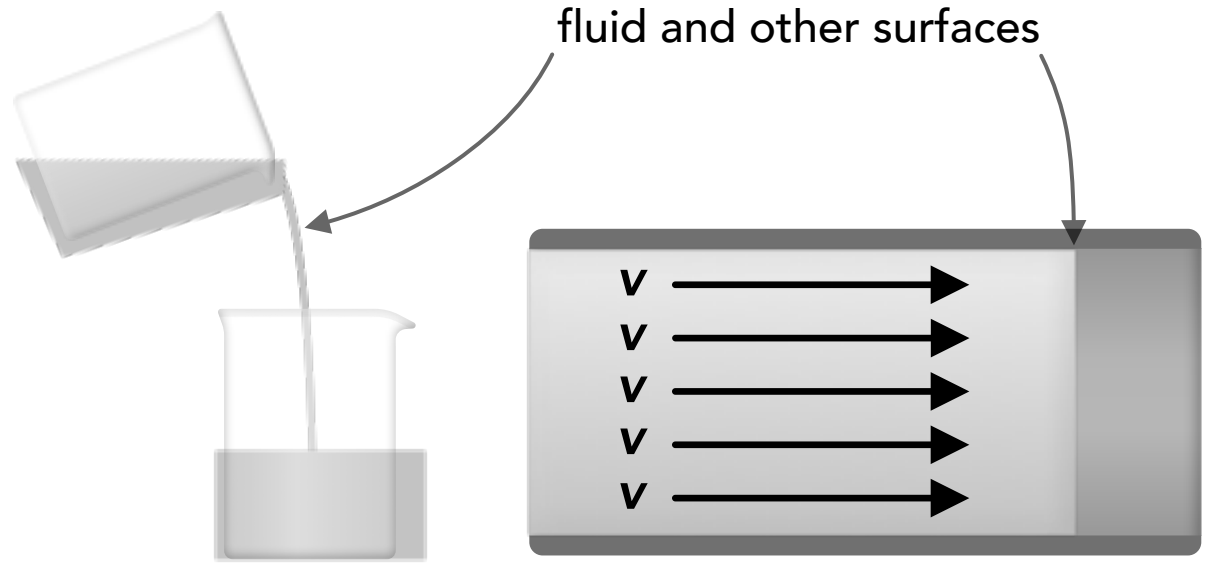
1. Completely incompressible

fluid volume and density do not change when a force is applied



2. No viscosity

no resistance to flow, no friction between fluid particles or between fluid and other surfaces



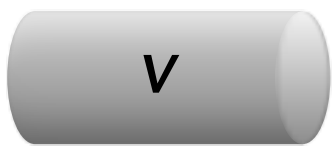
Volume

Variables		SI Unit
V	volume	m^3

- The **volume** of a substance (solid, liquid or gas) is the amount of three-dimensional space that substance occupies.
- The volume of a solid is just the volume of its shape (rectangular prisms, cylinders and spheres are common). The volume of a solid does not change (solids are nearly incompressible).
- The volume of a liquid depends on the shape of its container and the height of the liquid in the container. The volume of a given amount (mass) of liquid does not change regardless of the shape of the container or the pressure applied to it (liquids are nearly incompressible).
- A gas will expand to fill the volume of its container (assuming there is no other substance in the container). The volume of a gas can change when the shape or size of the container changes or when pressure is applied to it (gasses are compressible).

Solid

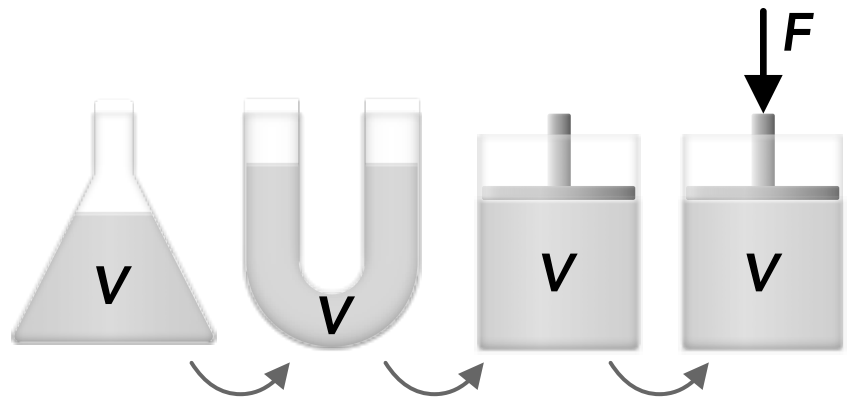
The volume of a solid is just the volume of its 3D shape. The volume of a solid **does not change** regardless of the forces applied to it.



$V = 2\ \text{L} = 2{,}000\ \text{cm}^3$

Liquid

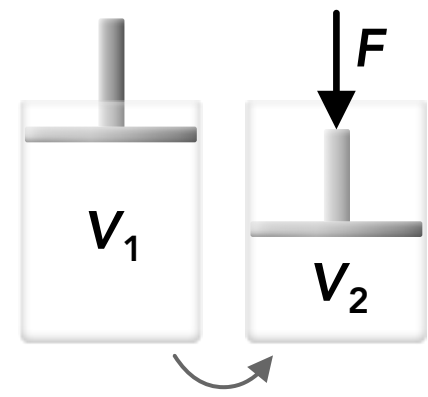
A liquid will flow to take the shape of its container. The volume of a given amount of a liquid **does not change** regardless of the container shape or the pressure applied to it.



$V = 1\ \text{L} = 1{,}000\ \text{cm}^3$

Gas

A gas will expand to **fill the volume of its container**. The volume (and density) of a gas **will change** when the container changes shape or size.



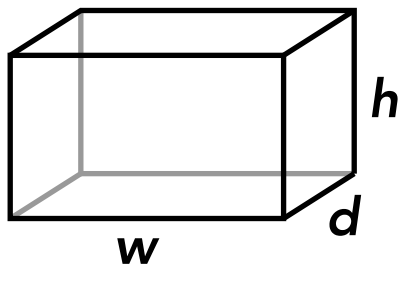
$V_1 = 1\ \text{L} = 1{,}000\ \text{cm}^3$
$V_2 = 0.5\ \text{L} = 500\ \text{cm}^3$

- The SI unit of volume is cubic meters (m^3) but there are many different units of volume that we might use, so we often have to convert between different volume units, especially when working with density.

Volume of different shapes:

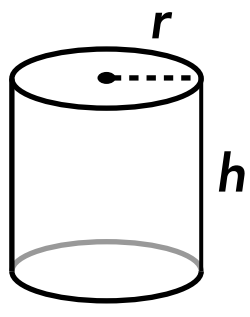
Rectangular prism

$V = wdh$



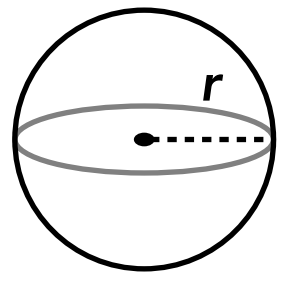
Cylinder

$V = \pi r^2 h$



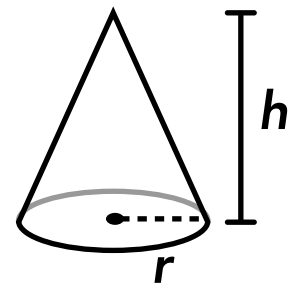
Sphere

$V = \frac{4}{3}\pi r^3$



Cone

$V = \frac{1}{3}\pi r^2 h$



Volume conversions:

$1\ \text{m}^3 = 1 \times 10^6\ \text{cm}^3$
$1\ \text{cm}^3 = 1{,}000\ \text{mm}^3$
$1\ \text{m}^3 = 1{,}000\ \text{L}$
$1\ \text{cm}^3 = 1\ \text{mL}$
$1\ \text{L} = 1{,}000\ \text{cm}^3$

Density

- **Density** is a property of a substance (solid, liquid or gas) that describes how much mass it has per unit of volume.
- We represent density with the greek letter ρ (rho, pronounced "row") and the SI unit of density is kg/m³.

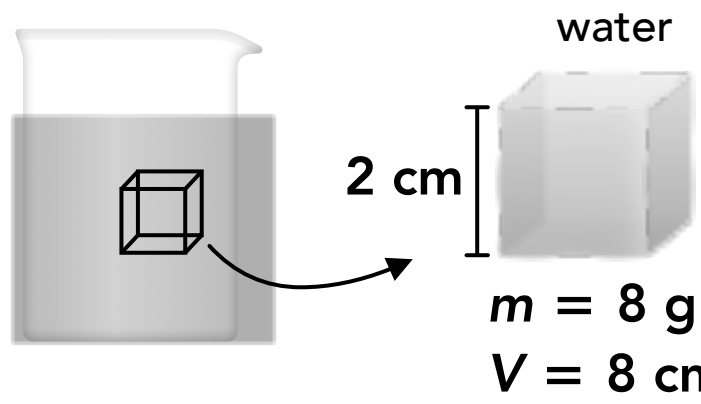
Values		Unit	Name
ρ_{water}	1000	kg/m³	density of water*
ρ_{ice}	916	kg/m³	density of ice**

*At 1 atm and 4°C
**At 0°C

Variables		SI Unit
ρ	density	kg/m³
m	mass	kg
V	volume	m³

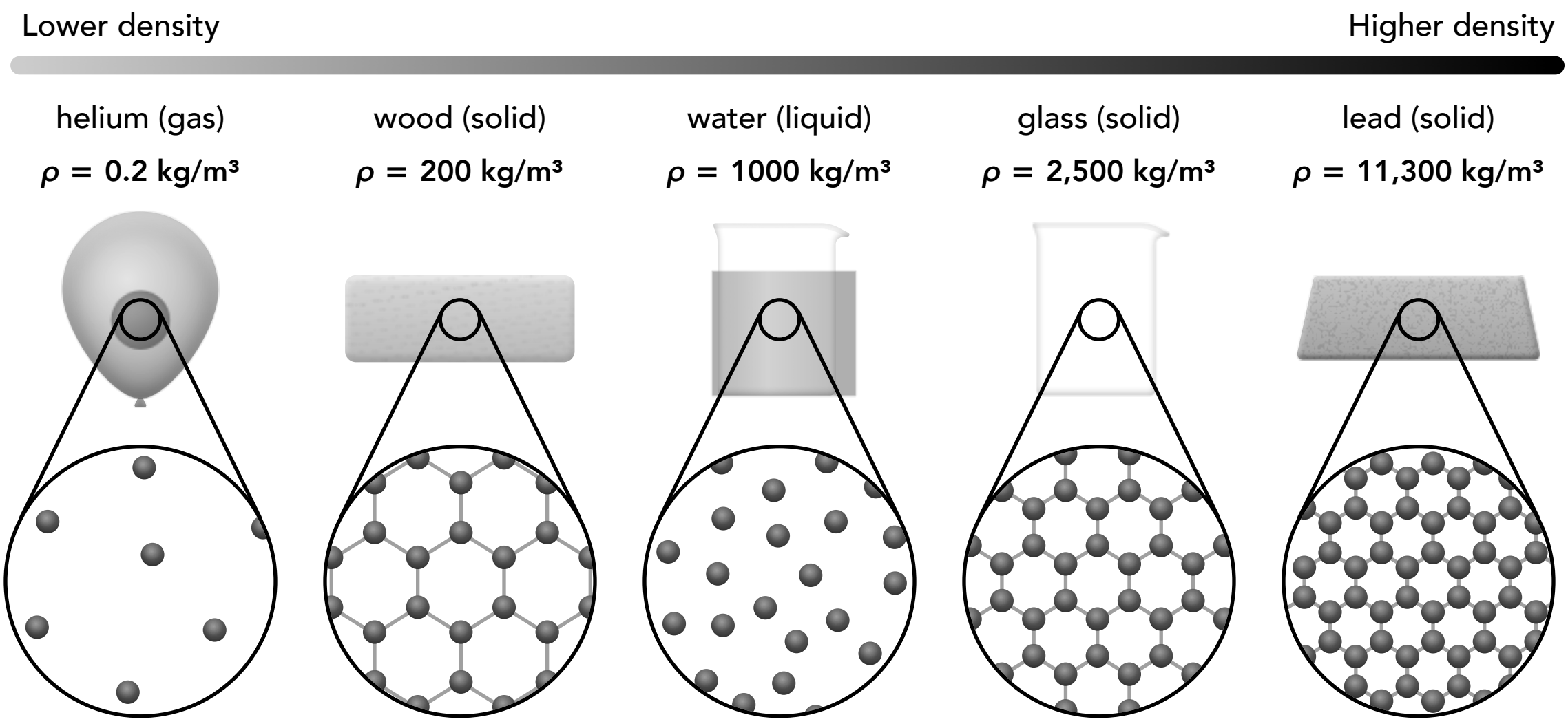
Density

$$\rho = \frac{m}{V}$$



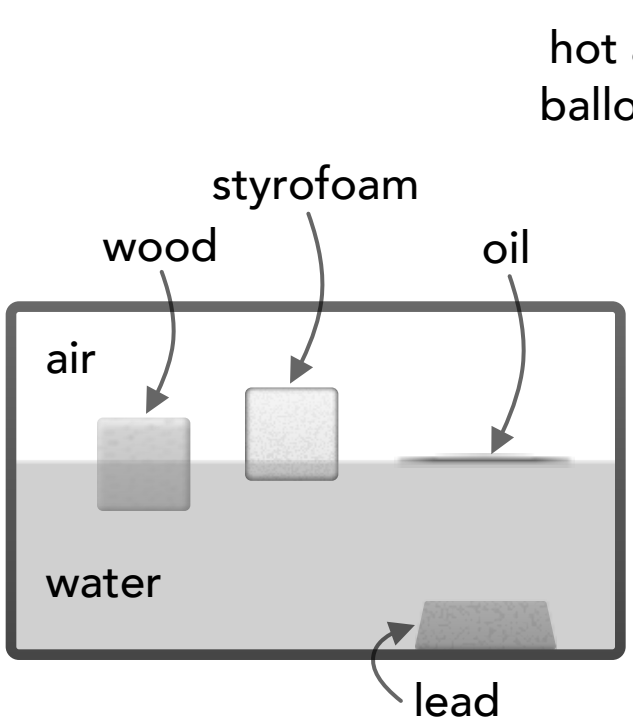
$$\rho = \frac{8\ g}{8\ cm^3} = 1\ g/cm^3 = 1000\ kg/m^3$$

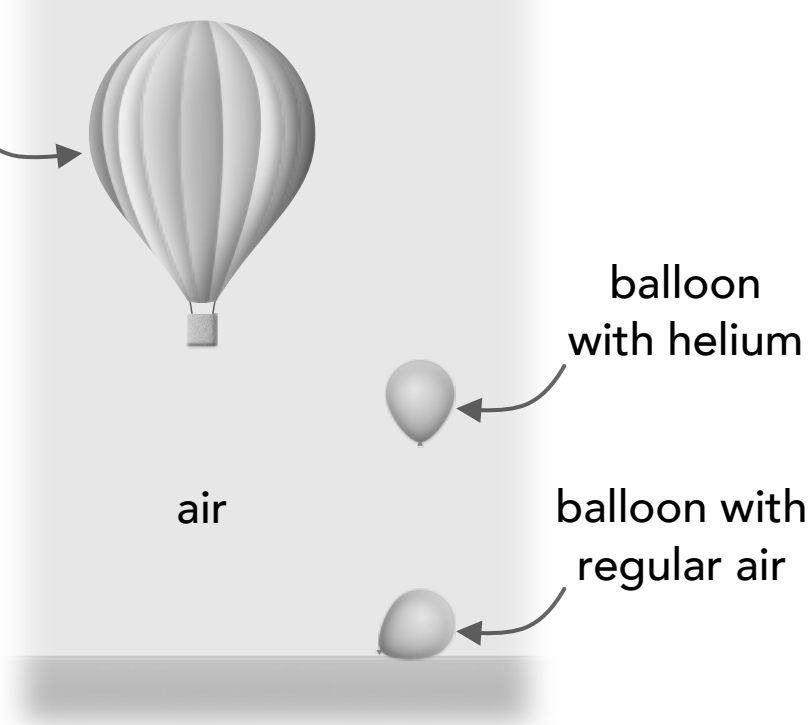
- The density of a substance is determined by the distance between the particles (atoms or molecules) and the mass of the atoms or molecules (the atomic mass of the elements).
- In general, a substance is more dense in the solid state than in the liquid state, and more dense in the liquid state than in the gas state. However, water is an exception to this trend and ice (solid water) is less dense than liquid water which causes ice to float in water instead of sink.



The amount of space between the particles, and the mass of the particles, affects the density of the material

- When two substances are in contact with each other **the substance or object with a lower density will float above the substance with a greater density**.
- This is caused by the **buoyant forces** acting on the substances or objects (covered in another section).
- For example, oil will float on top of water because oil is less dense than water, and lead will sink in water because lead is more dense that water. This is true regardless of the shape of the substances or objects (assuming that the object is solid and no air or other substance is contained within it, which would change its average density).
- This is the reason that a helium balloon floats while a balloon filled with regular air does not (helium is less dense than regular air), and is why a hot air balloon floats (hotter air is less dense than colder air).





Material	Density ρ (kg/m³)
Helium (gas, 27°C)	0.2
Water (gas, 107°C)	0.6
Air (gas, 80°C)	1.0
Air (gas, 20°C)	1.2
Styrofoam (solid)	30
Wood (solid)	200
Water (solid, ice)	916
Oil (liquid)	920
Water (liquid)	1,000
Glass (solid)	2,500
Iron (solid)	7,200
Lead (solid)	11,300

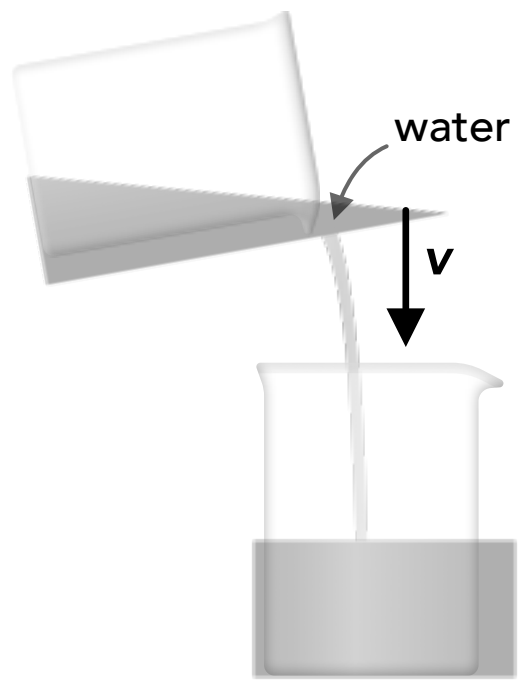
*Gasses at 1 atm

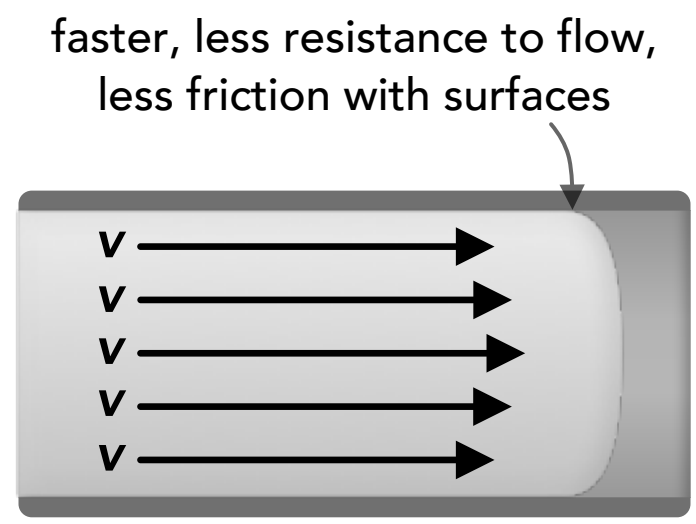
Viscosity

- **Viscosity** is a property of a fluid which describes its resistance to flow or the friction between particles.
- Fluids with lower viscosities may be referred to as "thin" and flow very quickly and easily (like water).
- Fluids with higher viscosities may be referred to as "thick" and flow very slowly (like honey or oil).
- Viscosity is an important property when studying fluid dynamics (how fluids flow) but we will not be covering it in more depth in this course.

Lower viscosity

- "Thin"
- Low friction/resistance
- Flows quickly





Higher viscosity

- "Thick"
- High friction/resistance
- Flows slowly