Matter

- The goal of Newton and his followers - to explain all phenomena mechanistically.
- The hypothesis was that everything in the universe is material - made of matter and comprises the matter.
  - Matter is everything tangible but field - will discuss fields later
  - Everything that has mass? No, field has mass...
- Some of these efforts were quite successful, so let us follow the history of application of Newton’s laws to matter.
- It is high time to apply what we learned in mechanics of material points to much more complex systems.
Richard Feynman:

“If in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words?”

“...All things are made of atoms - little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.”
Atoms

- Basically, Democritus suggested that every “piece of matter” can be divided into smaller parts, but there is a limit - atom - the smallest piece of matter.
- Actually, it is a little more complicated: atoms are the smallest “pieces” of elements - there are about 100 different kinds of elements and, therefore, atoms.
- Many atoms of one element grouped together represent pure element such as iron, phosphorus, or uranium. In these cases, atoms are the smallest pieces of matter.
- More often different (or same) kinds of atoms group together and form molecules, and then the molecules form a compound such as water, oxygen, carbon dioxide, salt, etc. Then the molecule is the smallest piece carrying the chemical property of matter.
- In principle, it is possible to chemically break any molecule to pieces - atoms...
How do we know?

- On the chemical level, the matter is made of atoms:
- Physical properties – just about to be discussed
- Chemical properties (reactions, compounds)
- Observations: from Brownian motion to atomic force microscope
What is inside the atom?
What explains physical properties of medium?

- What is inside the atom? We will discuss it later in the course
  - Briefly: a tiny nucleus carrying >99.95% of the atom’s mass, and an electron cloud surrounding it.
- A typical size of this cloud is from $10^{-10} \text{m}=0.1 \text{ nm}$ to 1 nm. If the distance between the two atoms is larger than several nanometers, they do not interact, if it is smaller, they do.
- We will first examine the macroscopic properties of matter and how they are related to the closeness of atoms in the medium
“Phases” of matter: GAS, LIQUID, SOLID

If atoms or molecules are reasonably far from each other, with very little interaction between them, we talk about a GAS.

If atoms or molecules are weakly bound together, but can still move relative to each other, we have a LIQUID.

If atoms are so strongly bound together that they can hardly move anymore, we talk of a SOLID.
The forces that hold atoms together to form molecules and atoms/molecules together to form liquids and solids are all electrical forces.

Example: Water ice.

Very strong forces hold together oxygen and hydrogen atoms to form a water molecule.

Water molecules are held together by weaker bonds, called 'hydrogen bonds' to form water ice.
Other examples from an “atomic point of view”:
INTERLUDE: Area and Volume

What is the area of a piece of paper that is 2 cm long and 2 cm wide?

\[ A = 2 \text{ cm} \times 2 \text{ cm} = 4 \text{ cm}^2 \]

What is the volume of a piece of wood that is 2 cm long, 2 cm deep, and 2 cm high?

\[ V = 2 \text{ cm} \times 2 \text{ cm} \times 2 \text{ cm} = 8 \text{ cm}^3 \]

What is the area of this figure?
In order to figure out what the area of an irregular shape is, we would have to count the number of unit squares that fill it. For example:

\[ \text{Area} \approx 18 \text{ cm}^2 \]

How could I improve my measurement?
MECHANICS OF MATTER:

Application of laws of mechanics to systems that have many interacting point-like particles.

If there are 2 particles it’s easy
If there are 3 - it’s more difficult
If there are 4 - it’s very difficult
If there are 5 - it’s hardly doable
...
If there are more particles than $10^{25}$ per m$^3$, then it may be easy again!

PRESSURE
Question:

I hold a 1 kg object in my hand. Then I put a sharp pin between my hand and the object. In both cases the force on my hand is the same (9.8 N). What is different between these cases?

How much force per area = \textbf{PRESSURE}

Measured in (SI unit) \hspace{1cm} 1 \text{ N/m}^2 = 1 \text{ Pascal}

Other units: \hspace{1cm} \text{psi} = \text{pounds per square inch} = 6,890 \text{ Pa}

1 atm = air pressure at sea level = 1 bar = 101,325 \text{ Pa} = 14.71 \text{ psi}

mm - millimeters?
Example:
You are holding an object (1 kg) with a bottom area of 100 cm\(^2\) = 0.01 m\(^2\). What is the pressure?

Pressure = \( \frac{F}{A} = \frac{1 \text{ kg} \times 9.8 \text{ m/s}^2}{0.01 \text{ m}^2} = 980 \text{ Pa} \)

Now you put a pin in between the object and your hand. Area of end of pin:
1 mm\(^2\) = 0.000001 m\(^2\).

Pressure = \( \frac{9.8 \text{ N}}{0.000001 \text{ m}^2} = 9,800,000 \text{ Pa} \)!!
Which object exerts the most pressure, which the least?

1 lb, area that touches floor: 1 in x 1 in

1 lb, ½ in x ½ in

1 lb, 1 in x 2 in

4 lb, 2 in x 2 in

1 lb, 1 in x 2 in

1 lb, ½ in x ½ in
How to sit on nails

- When you sit down, the force you are acting on your support whether it is one nail or a nail carpet is the same (~mg)
- The area is certainly different, therefore the pressure is different too. The reaction force is split decomposed in many reaction forces.
- If each reaction force is small enough - it is inversely proportional to the amount of nails - it does not hurt you.
• Mass is proportional to the volume, if the material is the same.

• Mass depends on the material and can be different between two samples of different material even if the volume is the same.

Density: Mass divided by volume:

A mass of a unit volume of a certain material

For example: The mass of 1 cm$^3$ of water is 1 gram.

$D_{\text{water}} = 1\text{g/cm}^3$

Density $= \frac{m}{V}$
Question:

I have a piece of wood 1 cm x 1 cm x 1 cm and another one 2 cm x 2 cm x 2 cm. What is the relation between their masses?

The amount of material, and therefore its mass is directly proportional to its volume:

\[
\frac{m_1}{m_2} = \frac{V_1}{V_2} = \frac{1 \times 1 \times 1 \text{ cm}^3}{2 \times 2 \times 2 \text{ cm}^3} = \frac{1}{8}
\]

\[
\frac{m_1}{V_1} = \frac{m_2}{V_2} = D
\]

Density, D, kg/m³
Example:
You have a piece of wood and a piece of steel. Both are 1cm x 1cm x 1cm. How do their masses compare?

\[ m_{\text{wood}} = D_{\text{wood}} \cdot V \]
\[ m_{\text{iron}} = D_{\text{iron}} \cdot V \]
\[ m_{\text{wood}} < m_{\text{iron}} \implies D_{\text{wood}} < D_{\text{iron}} \]
Density is a “materials property”
It has specific values for different types of materials. Can be used to identify materials.

Examples:

- **Aluminum**: $2.7 \text{ g/cm}^3$ \implies A 1cm x 1cm x 1cm piece of Al has a mass of 2.7 grams.

- **Steel**: $7.8 \text{ g/cm}^3$ \implies A 1cm x 1cm x 1cm piece of Steel has a mass of 7.8 grams.

- **Water**: $1.0 \text{ g/cm}^3$
Weight of the water acting on a diver: $Mg = D V g$ 

$= D A h g$

PRESSURE: $p = F/A = D h g$

For this example, $h = 2.25 \text{ m}$

$D_{\text{water}} = 1000 \text{ kg/m}^3$

$p = 1000 \times 2.25 \times 9.8$ 

$= 2.2 \times 10^4 \text{ Pa}$

In psi?

$p = \frac{2.2 \times 10^4}{6890}$

$= 3.2 \text{ psi}$
Pressure in liquids linearly depends on depth
Pressure in liquids in the field of gravity = Dgh

Another example:
What is the pressure at a 5m depth in water?
p = 1000 kg/m³ × 9.8 m/s² × 5 m = 49,000 Pa

In the previous example we got about 22,000 Pa
That’s less than air pressure!! What’s wrong here?
We need to include air pressure.

\[ p_{\text{total}} = \rho g h + p_{\text{air}} \]

When we talk about the pressure that is additional to the air pressure, we talk of ‘gauge pressure’.
EXAMPLE:

Tire pressure. Air pressure is 14 psi. Your tire pressure gauge measures 26 psi. What is the total pressure in your tires?

\[ p_{\text{inside}} = p_{\text{gauge}} + p_{\text{atm}} \]

Gauge pressure is 26 psi. Total pressure = gauge pressure + air pressure = 40 psi

What happens if \( p_{\text{atm}} \) suddenly increases?

\( p_{\text{in}} \) does not change!

\[ p_{\text{gauge}} = p_{\text{in}} - p_{\text{atm}} \]

\( p_{\text{gauge}} \) DECREASES!
PRESSURE IN A GAS

QUESTION:
You put air into a tight container and take it to the moon. Is there pressure on the walls of the container?

Why would a gas, that is not solid, exert a pressure in the first place?
Gas molecules collide with the walls, a gazillion times a second. Each collision imparts a small force for a small time on the walls. Averaged over gazillions of collisions per second, this adds up to a pressure. $f = \frac{\Delta(mv)}{\Delta t}$
The ideal gas: elastic tiny spherical particles

Elastic, hence the kinetic energy is conserved.

Temperature is defined as this total kinetic energy of the atoms with some coefficient (to measure it in degrees).

Then, if we know the number of atoms, we can find the average kinetic energy per atom, and therefore the average speed and magnitude of \( mv \) per atom.

\[
F = \frac{\Delta (mv)}{\Delta t}...
\]

The result for the pressure is:

\[
p = \frac{N}{V} kT
\]

where \( k \) is a universal constant

\( N \) is a number of molecules

\( V \) is a volume

\( T \) is a temperature
The ideal gas law:

Pressure ✧ if

Temperature ✧ (molecules move faster)

Volume ✧ (molecules have less space, therefore hit walls more often)

Number ✧ (more molecules will hit walls more often)

\[ p = \frac{N}{V} kT \quad \text{or} \quad p = D_N kT \]
Atmospheric pressure

Normal pressure at sea level is:

1 atm = 14.7 psi = 101,293 Pa = 760 mm Hg

101293 Pa = D_{Hg}gh = 13,600 \times 9.8 \times h = 133280 \times h

h = \frac{101293}{133280} = 0.760 \text{ m} = 760 \text{ mm}
Mercury... what about water? How high the water will rise?

1 atm = 101293 Pa = D g h = 1,000 x 9.8 x h
h = 101,293/1,000/9.8 = 10.34 m

10.34 m = 33.9 ft

It is not possible to pull water higher than 10.34 m at normal atmospheric pressure!

Can trees be higher than 10.34 m?
Air pressure decreases with altitude.
QUESTION:

You have a container filled with water. Does the fluid pressure only act on the bottom of the container?

1. Yes, since pressure is due to the weight of the water.

2. No, since water is a fluid and it can spread, therefore pressure also acts on the walls.
Liquids can spread, and cannot be compressed.
Pressure acts not only on the bottom of the container but on all sides of the container.
PASCAL’S PRINCIPLE

If liquid is enclosed, pressure will be transmitted undiminished to all parts of the fluid and the walls of the container.
APPLICATION:
HYDRAULICS

(a) Master cylinder
   Brake pedal
   Wheel cylinder
   Brake pad
   Disc (rotor)

(b) Tire
   F
   Brakes applied
Questions:
Why does wood float on water and rocks sink?
Why does wood not float in air?
Why do helium balloons rise but (cold) air balloons sink?
Why do hot air balloons rise?

\[
p_T = Dgh_T \quad \Rightarrow \quad F_T = p_T A = Dgh_T A
\]
\[
p_B = Dgh_B \quad \Rightarrow \quad F_B = p_B A = Dgh_B A
\]
\[
F_{buoyancy} = F_B - F_T = Dgh_B A - Dgh_T A
\]
\[
= Dg(h_B - h_T) A = DgHA
\]
\[
= DgV = M_{\text{liquid}} g = W_{\text{liquid}}
\]

\[
F_{buoyancy} = W_{\text{displaced liquid}}
\]
A fluid will exert an upward force on an object equal to the weight of the fluid displaced by the object.

This force is called the buoyant force.

\[ F_b = D_L g V \]
EXAMPLE:

Estimate the buoyant force on a person diving.

5’ 11” = 180 cm, 180 lbs = 82 kg

Let’s say

\[ V = 180 \text{ cm} \times 450 \text{ cm}^2 = 81,000 \text{ cm}^3 = 81 \text{ L} \]

\[ F_b = 1 \text{ kg/L} \times 9.8 \text{ m/s}^2 \times 81 \text{ L} = 794 \text{ N} \]

Compare: Weight of person:

\[ W = 82 \text{ kg} \times 9.8 \text{ m/s}^2 = 804 \text{ N} \]
Archimedes example:
A golden? Crown
When we weigh the crown in air its weight is 6.000 lb, when we weigh it submerged in water its weight is 5.689 lb. Is the crown made of gold?

\[
\begin{align*}
W_{\text{submerged}} &= W_{\text{out}} - D_w g V \\
V &= \left( W_{\text{out}} - W_{\text{submerged}} \right) / g / D_w \\
D &= W_{\text{out}} / g / V = W_{\text{out}} / \left( W_{\text{out}} - W_{\text{submerged}} \right) D_w = \frac{6}{6 - 5.689} \times 1 \frac{g}{cm^3} = 19.293 \frac{g}{cm^3}
\end{align*}
\]

The density of gold is 19.3 \( \frac{g}{cm^3} \)
Archimedes problem about a crown – the way to determine the density of an object

\[ D = D_{\text{liquid}} \left( \frac{W_{\text{out}}}{W_{\text{out}} - W_{\text{submerged}}} \right) = D_{\text{liquid}} \frac{W_{\text{out}}}{\Delta W} \]

Floating objects - what is the condition?
• **Example**: what does it mean to float? “A boat is floating.” The boat’s mass is 50 tons. How much water is displaced?

Exactly 50 tons. The buoyancy force must be equal to the force of gravity of the boat for the boat to be static.

• If there is no equality, there must be acceleration:

A 2 liter He balloon $ma = DVg - mg$, therefore it flies upwards if you let go. If you do not, then $T + mg = DVg$

The tension force keeps it tied.

• If the average density of an object is less than the density of liquid, it floats - it rises to the surface to displace less liquid to make gravitational and buoyancy forces equal
What if the fluid is moving?
Does the fluid pressure change?

QUESTION:

How does the pressure in the more narrow pipe compare to the pressure in the wider pipe?

1. It will be higher.
2. It will be lower.
3. It will be the same.
Strangely enough, the pressure in the narrower section is LOWER than in the wider section!

BERNOULLI'S PRINCIPLE:

For a fluid undergoing steady flow, the pressure is lower where the fluid is flowing faster.

\[ p + Dgh + \frac{1}{2} Dv^2 = \text{constant} \]
Examples of Bernoulli principle:

**Magnus effect:** lift force due to pressure difference below and above the rotating cylinder (or ball) in air (water) flow.

The same principle causes the lift force in under-sonic airplanes:

The speed “above” the wing is on the average larger higher than “below”.