DTU

47201 Engineering thermodynamics

Module 1a

Teachers and Teaching Assistants

Andrea
Teacher

Apurv
Teacher

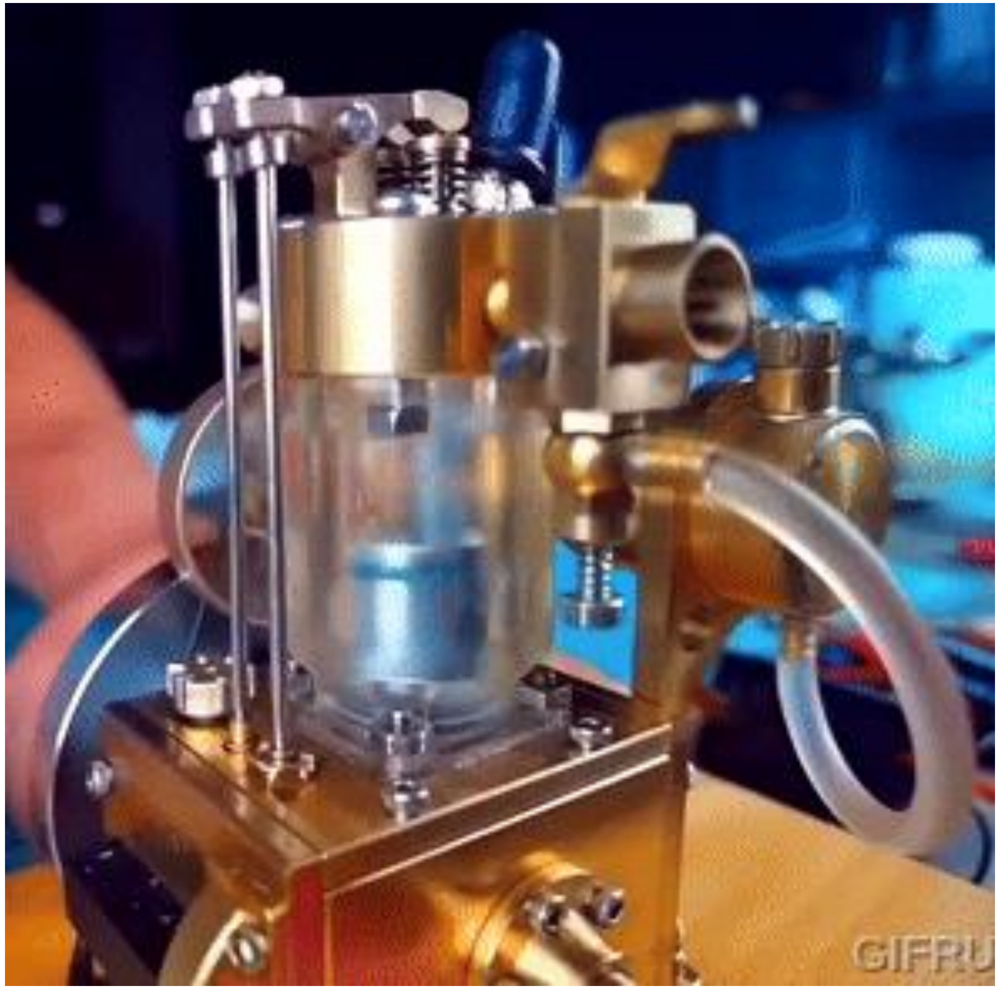
Cenk
Teaching Assistant

Hendrik
Teaching Assistant

Javid
Teaching Assistant

What is thermodynamics?

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy. [The usual definition]

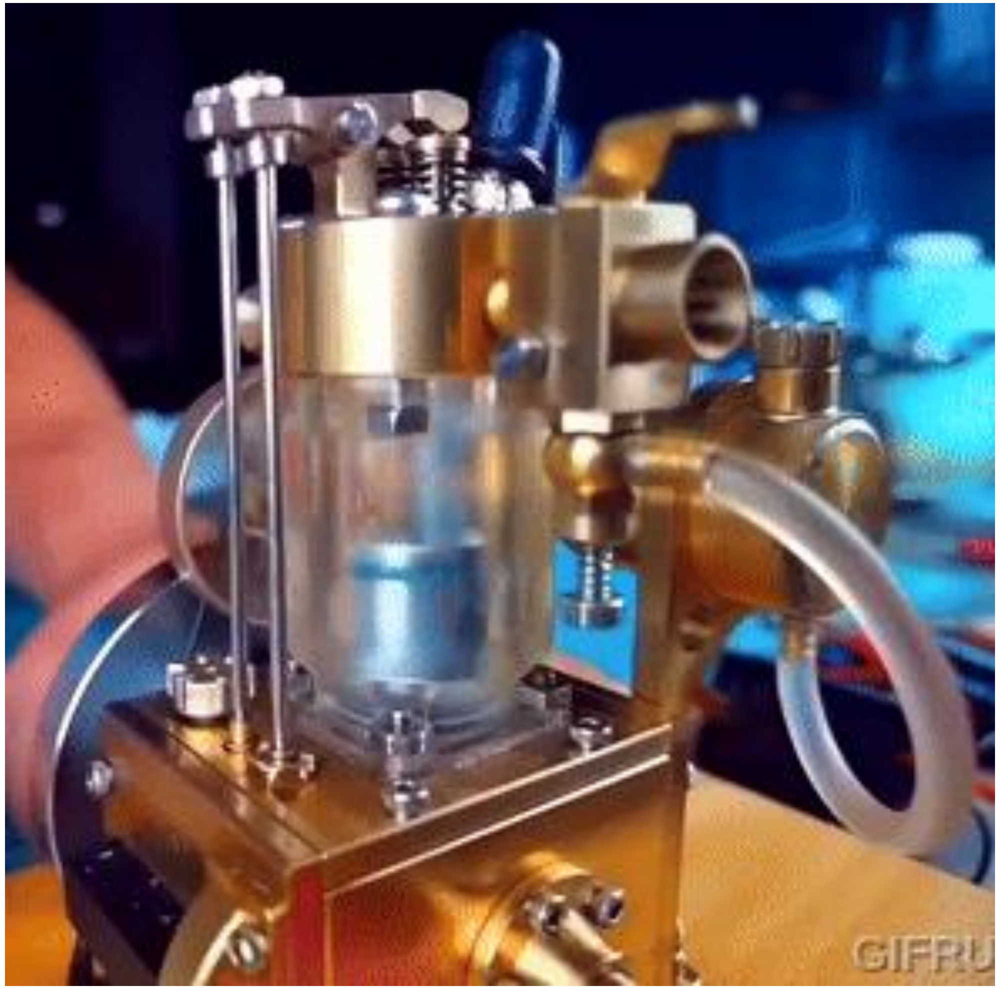


https://youtu.be/cBRo1uH5H6Y?feature=shared

What is thermodynamics?

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

- Thermodynamics is the study of large systems where, due to the large number of identical composing sub-systems, statistical methods and probability theory can be applied to reliably predict some macroscopic properties of the whole system.

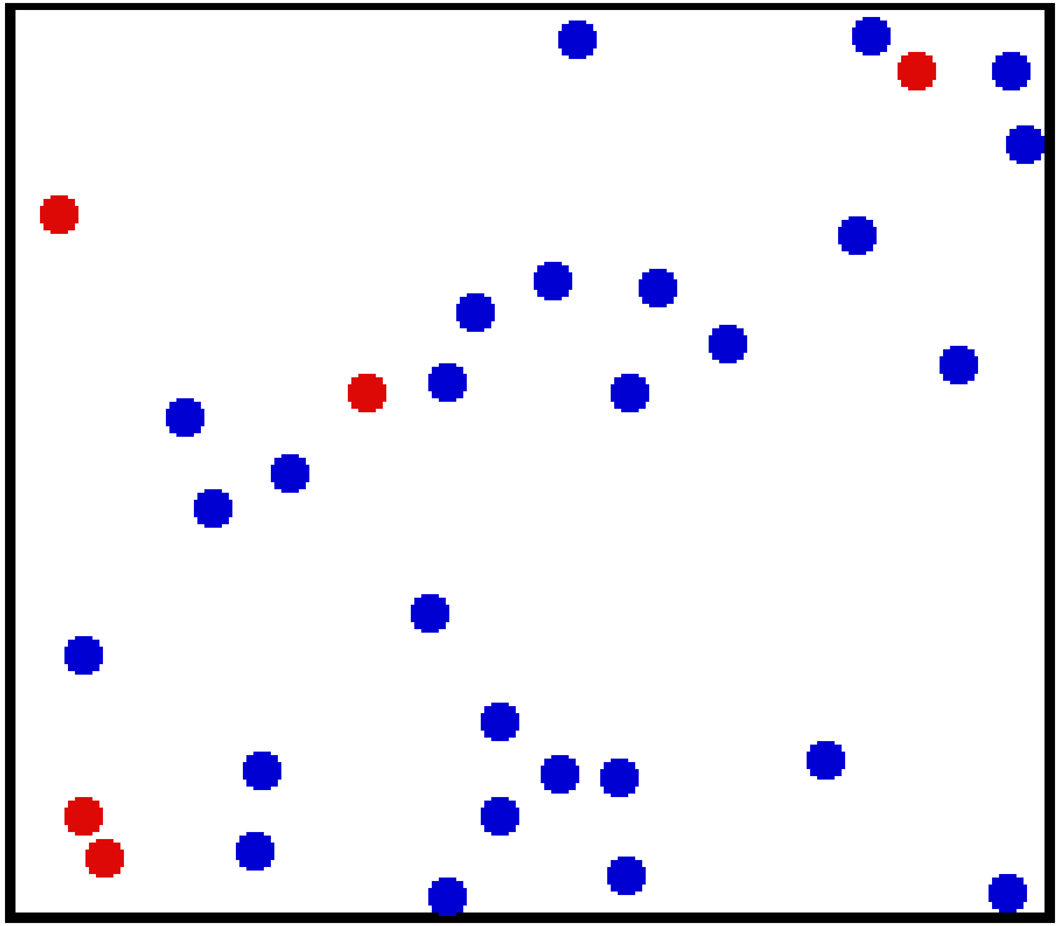


https://youtu.be/cBRo1uH5H6Y?feature=shared

Molecules in a gas

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

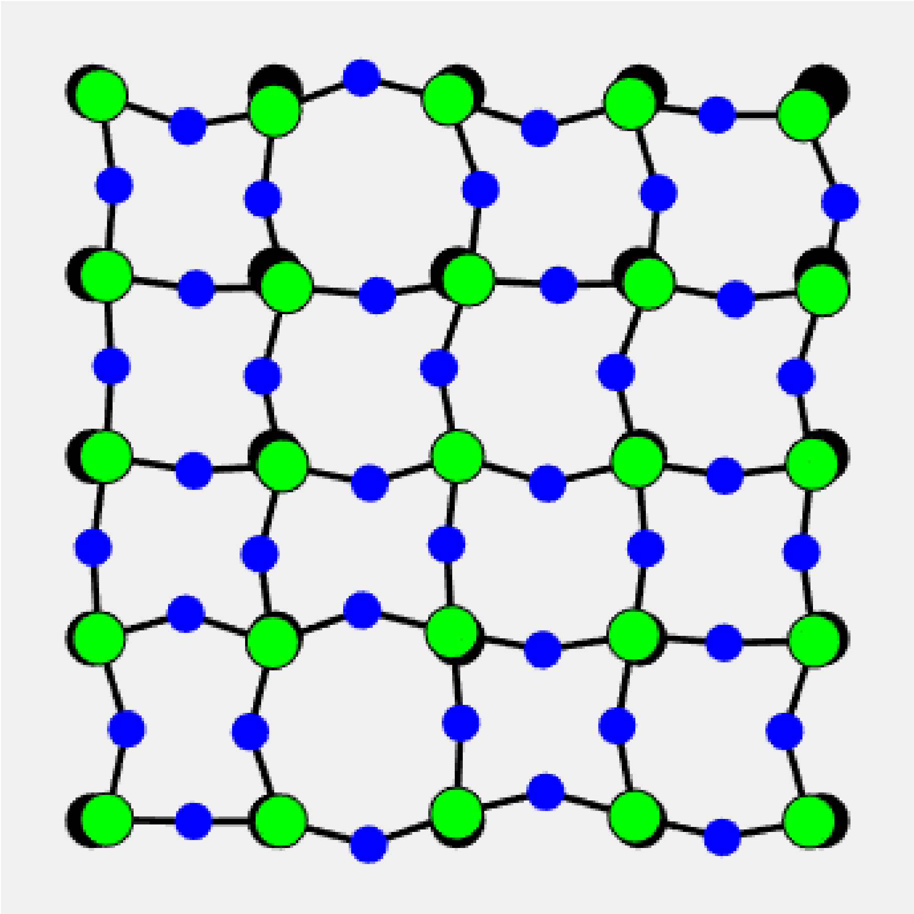
- Thermodynamics is the study of large systems where, due to the *large number of identical composing sub-systems*, statistical methods and probability theory can be applied to reliably predict some macroscopic properties of the whole system.



Atoms in a solid

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

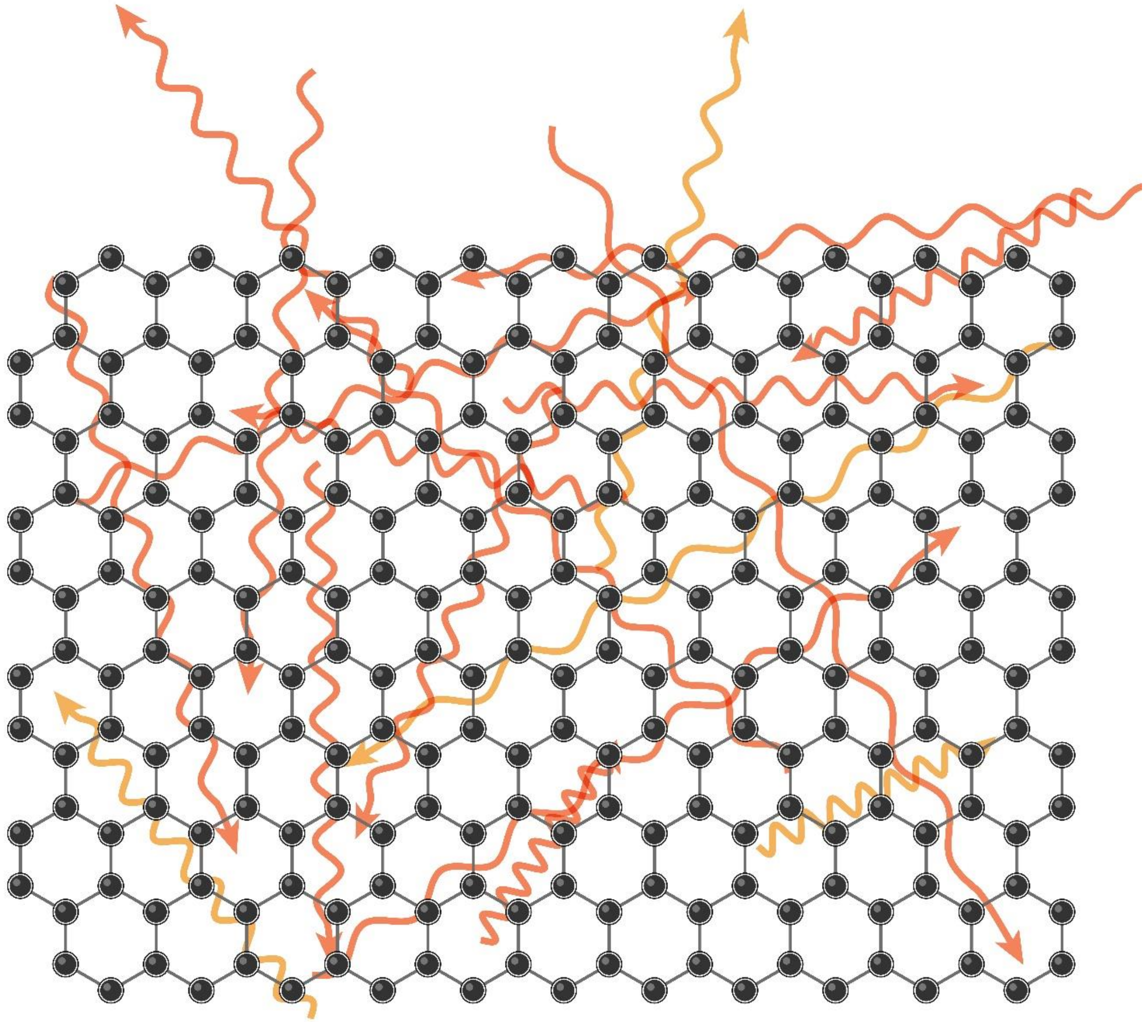
- Thermodynamics is the study of large systems where, due to the *large number of identical composing sub-systems*, statistical methods and probability theory can be applied to reliably predict some macroscopic properties of the whole system.



Thermal photons

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

- Thermodynamics is the study of large systems where, due to the *large number of identical composing sub-systems*, statistical methods and probability theory can be applied to reliably predict some macroscopic properties of the whole system.



…

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

- Thermodynamics is the study of large systems where, due to the *large number of identical composing sub-systems*, statistical methods and probability theory can be applied to reliably predict some macroscopic properties of the whole system.

Other examples:

- conduction electrons in a metal
- molecules undergoing a chemical reaction in a solution
- spins in a magnetic material
- …

What is thermodynamics?

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

- Thermodynamics is the study of large systems where, due to the large number of identical composing sub-systems, statistical methods and probability theory can be applied to reliably predict some macroscopic properties of the whole system.

Thermodynamics doesn’t describe any specific kind of interaction, fundamental force, or physical phenomenon.

It is transversal: it’s relevant and linked to many areas of physics. Probably all?

It describes the consequences of the fundamental *randomness* that is intrinsic in many situations.

What is thermodynamics?

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

- Thermodynamics is the study of large systems where, due to the large number of identical composing sub-systems, statistical methods and probability theory can be applied to reliably predict some macroscopic properties of the whole system.

In all the examples we have seen:

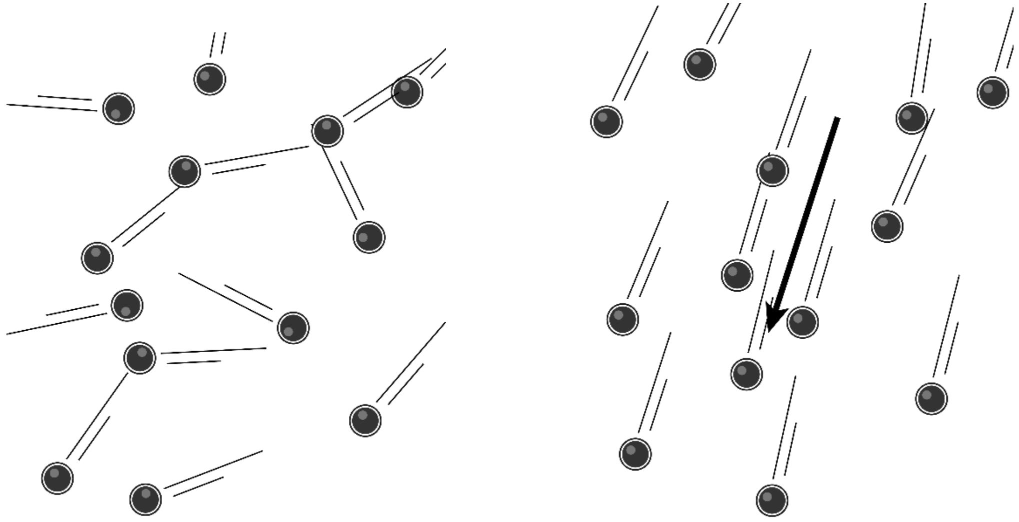
- The specifics of the interaction between subsystems are not the main interest.
  E.g.: in a gas, it's enough to say that molecules bounce on each other.
- The whole system has some energy, but its randomly subdivided into the energy of the composing subsystems.

It describes the consequences of the fundamental *randomness* that is intrinsic in many situations.

What is thermodynamics?

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

- Thermodynamics is the study of large systems where, due to the large number of identical composing sub-systems, statistical methods and probability theory can be applied to reliably predict some macroscopic properties of the whole system.



random ordered

- The whole system has some energy, but its randomly subdivided into the energy of the composing subsystems.

$$K = \sum_i m_i v_i^2$$

Total kinetic energy

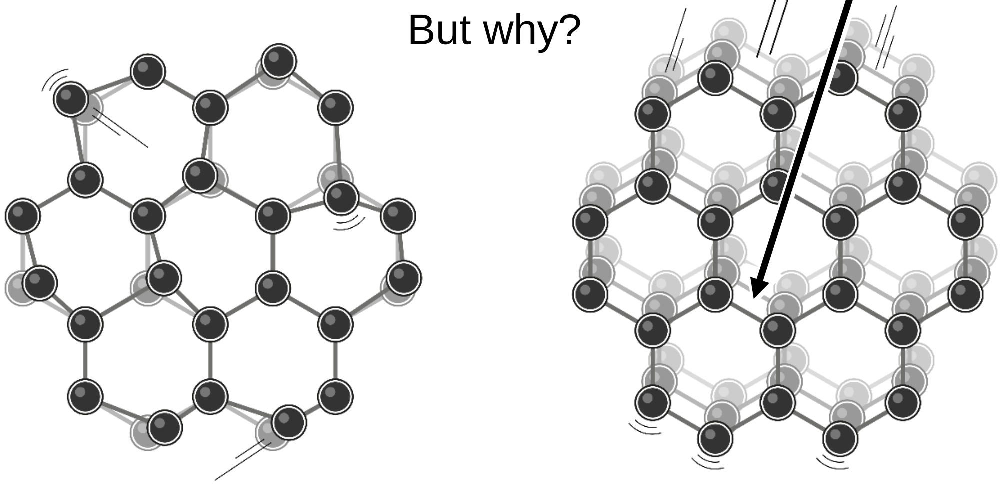
What is thermodynamics?

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

- Thermodynamics is the study of large systems where, due to the large number of identical composing sub-systems, statistical methods and probability theory can be applied to reliably predict some macroscopic properties of the whole system.

The two situations are very different.

But why?



random ordered

- The whole system has some energy, but its randomly subdivided into the energy of the composing subsystems.

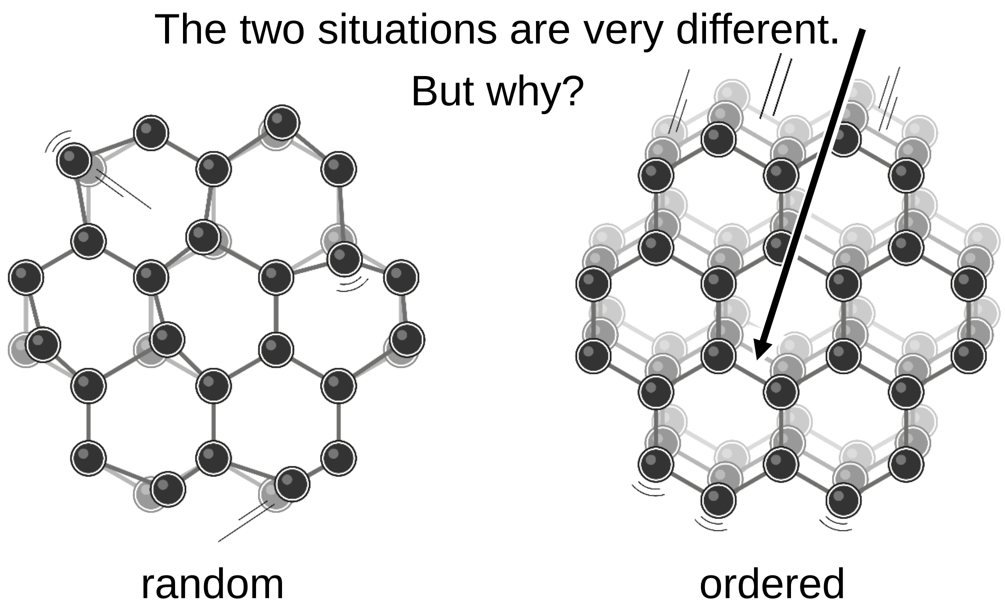
$$K = \sum_i m_i v_i^2$$

Total kinetic energy

What is thermodynamics?

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

- Thermodynamics is the study of large systems where, due to the large number of identical composing sub-systems, statistical methods and probability theory can be applied to reliably predict some macroscopic properties of the whole system.



In the random case, it is more difficult to harvest and utilize the energy.

$$K = \sum_i m_i v_i^2$$

Total kinetic energy

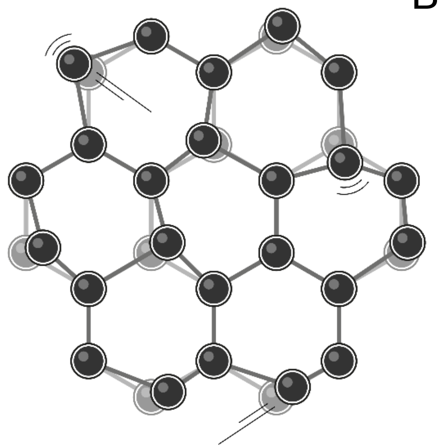
The two situations are very different.

But why?

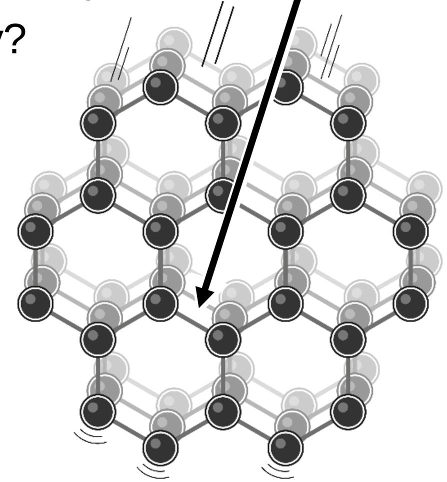
What is thermodynamics?

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

- Thermodynamics is the study of large systems where, due to the large number of identical composing sub-systems, statistical methods and probability theory can be applied to reliably predict some macroscopic properties of the whole system.



random



ordered

In the random case, it is more difficult to harvest and utilize the energy.

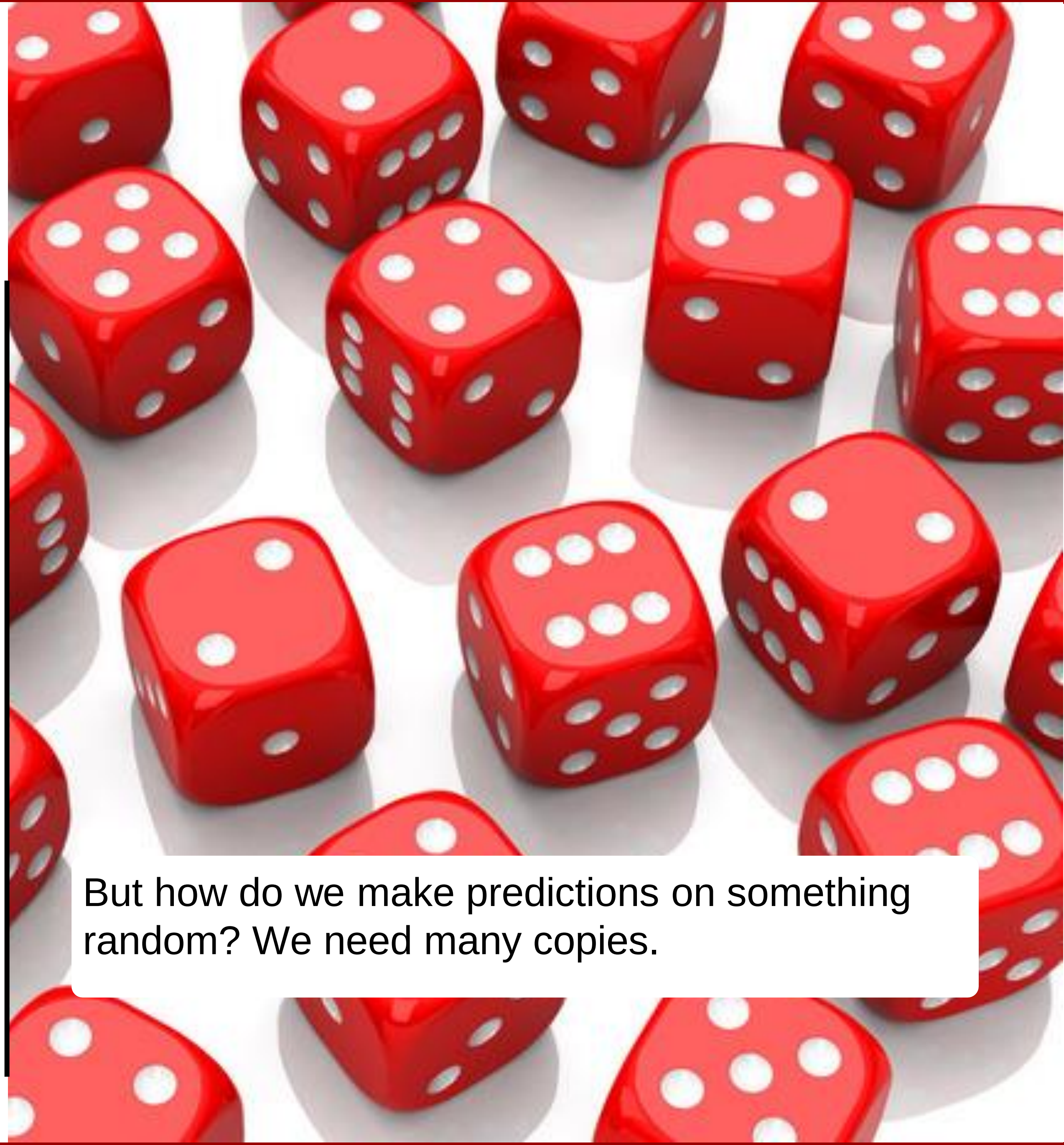
This is the main subject of thermodynamics.

But how do we make predictions on something random?

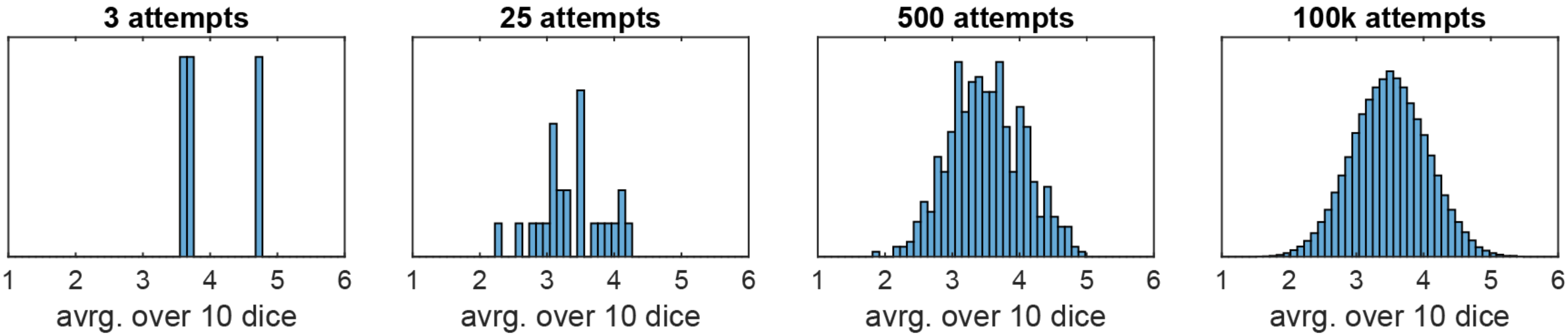
Large numbers

- Thermodynamics studies the conversion between heat and work - and the relation of these concepts with energy, temperature and entropy.

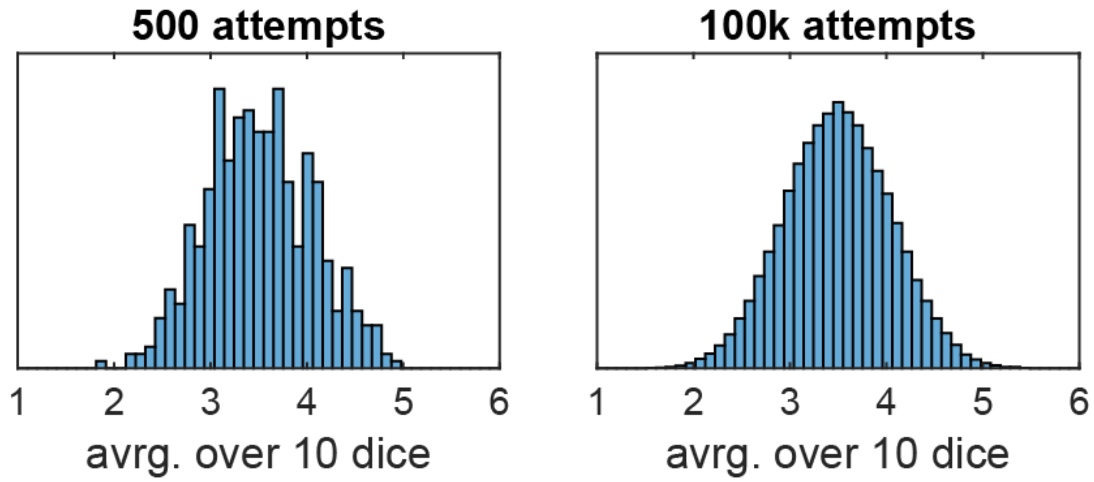
- Thermodynamics is the study of large systems where, due to the large number of identical composing sub-systems, statistical methods and probability theory can be applied to *reliably predict* some macroscopic properties of the whole system.



But how do we make predictions on something random? We need many copies.



- Thermodynamics is the study of large systems where, due to the large number of identical composing sub-systems, statistical methods and probability theory can be applied to *reliably predict* some macroscopic properties of the whole system.



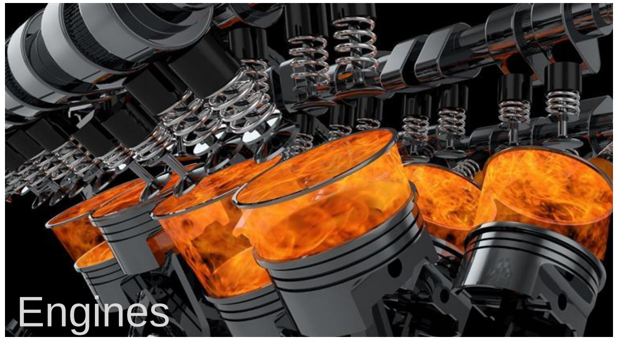
- Thermodynamics is the study of large systems where, due to the large number of identical composing sub-systems, statistical methods and probability theory can be applied to *reliably predict* some macroscopic properties of the whole system.

This is why the second law of thermodynamics seems to be so hostile from our perspective.

It expresses the ungenerous laws of randomness and probability: things are very likely to go in the most likely way

This limits the efficiency of our attempts of converting energy from one form to another.

Engineering applications of thermodynamics



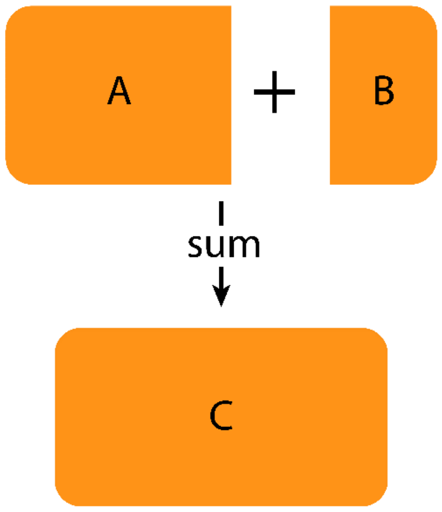
Which properties are we interested about?

- Thermodynamics is the study of large systems where, due to the large number of identical composing sub-systems, statistical methods and probability theory can be applied to reliably predict some *macroscopic properties* of the whole system.

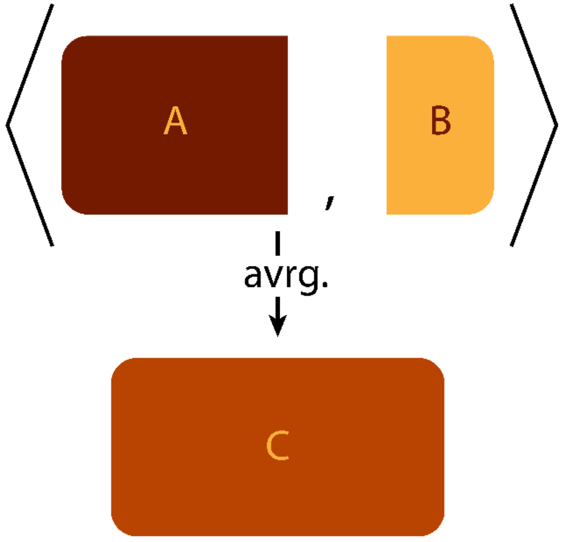
- Microscopic properties (not known):
  Examples:
  - velocity of each particle in a gas
  - frequency of each photon emitted by a body

- Macroscopic properties (predictable):
  Examples:
  - Total energy
  - Average temperature
  - Total amount of substance
  - …

Systems and properties: extensive and intensive

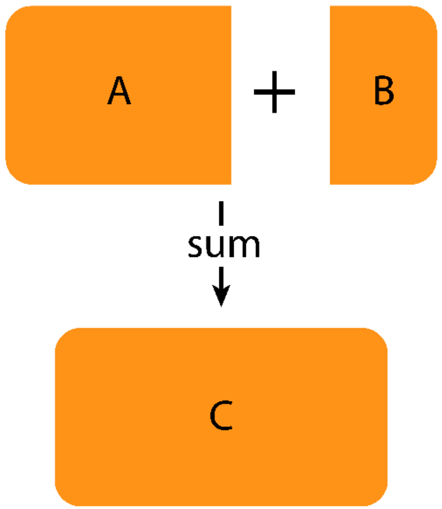


When I compose two systems A and B
The *extensive* properties are *summed*



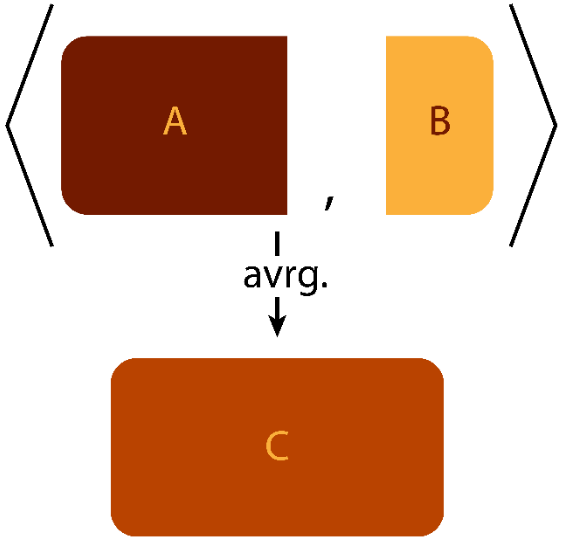
When I compose two systems A and B
The *intensive* properties are *averaged*

Systems and properties: extensive and intensive



When I compose two systems A and B
The *extensive* properties are *summed*

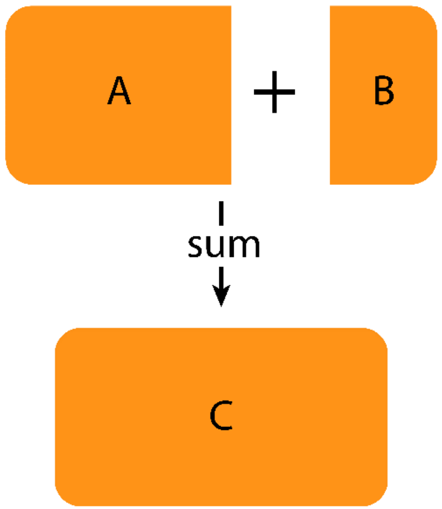
Example: (total) mass

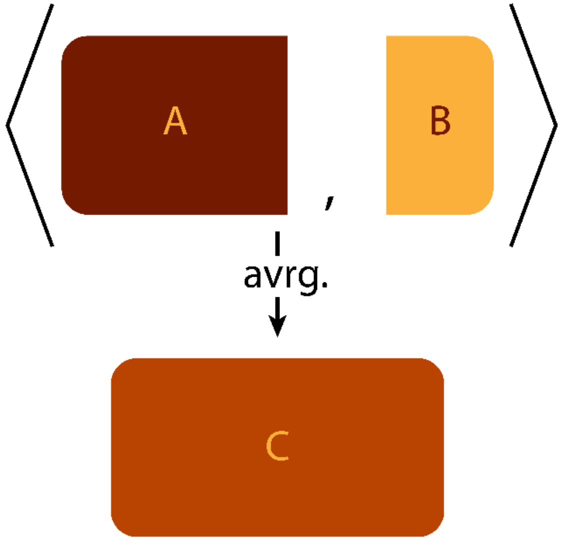


When I compose two systems A and B
The *intensive* properties are *averaged*

Example: (average) mass density

Systems and properties: extensive and intensive



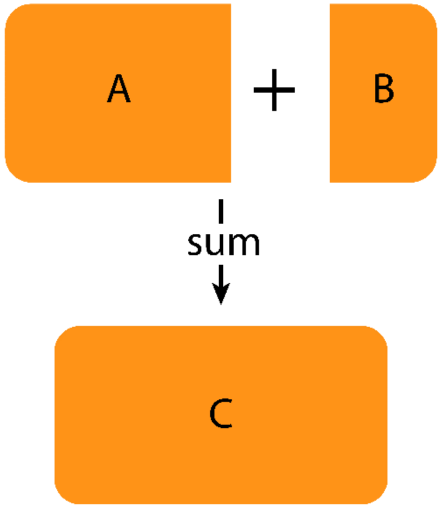


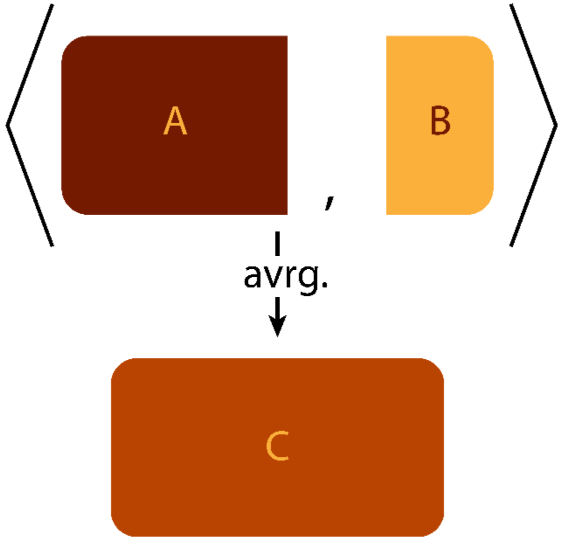
When I compose two systems A and B
The *extensive* properties are *summed*

When I compose two systems A and B
The *intensive* properties are *averaged*

Example: (total) mass —— density → Example: (average) mass *density*

Systems and properties: extensive and intensive





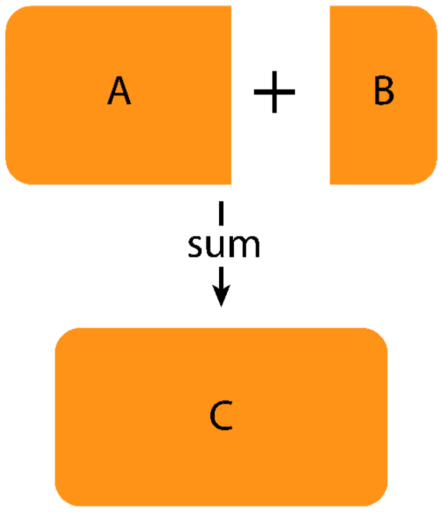
When I compose two systems A and B
The *extensive* properties are *summed*

When I compose two systems A and B
The *intensive* properties are *averaged*

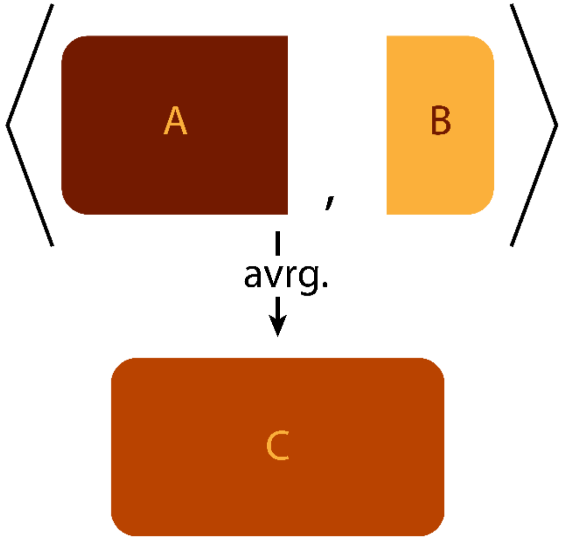
Example: (total) mass —— density ——→ Example: (average) mass *density*

Example: (total) charge —— density ——→ Example: (average) charge *density*

Systems and properties: extensive and intensive



When I compose two systems A and B
The *extensive* properties are *summed*

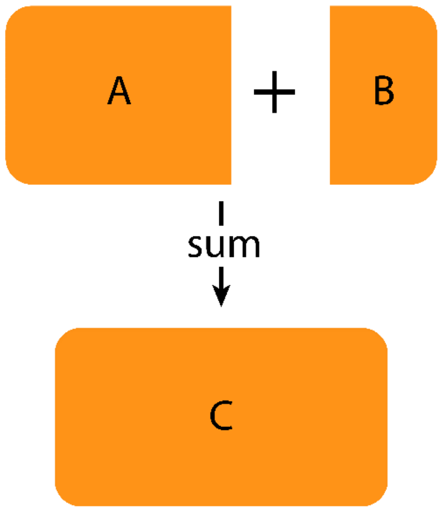


When I compose two systems A and B
The *intensive* properties are *averaged*

For intensive properties, it is also relevant to consider the value in each point.

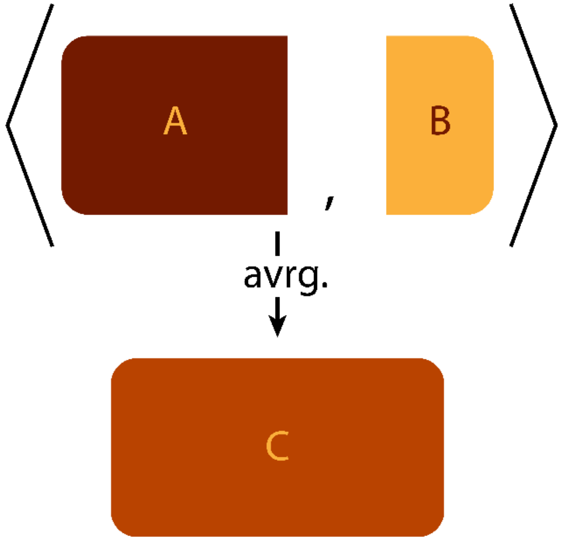
Example: (total) charge —— density ⟶ Example: charge density *at point x*

Systems and properties: extensive and intensive



How do we classify these?

Energy
Temperature
Volume
Pressure
Entropy
Heat capacity
Specific heat capacity
Energy density



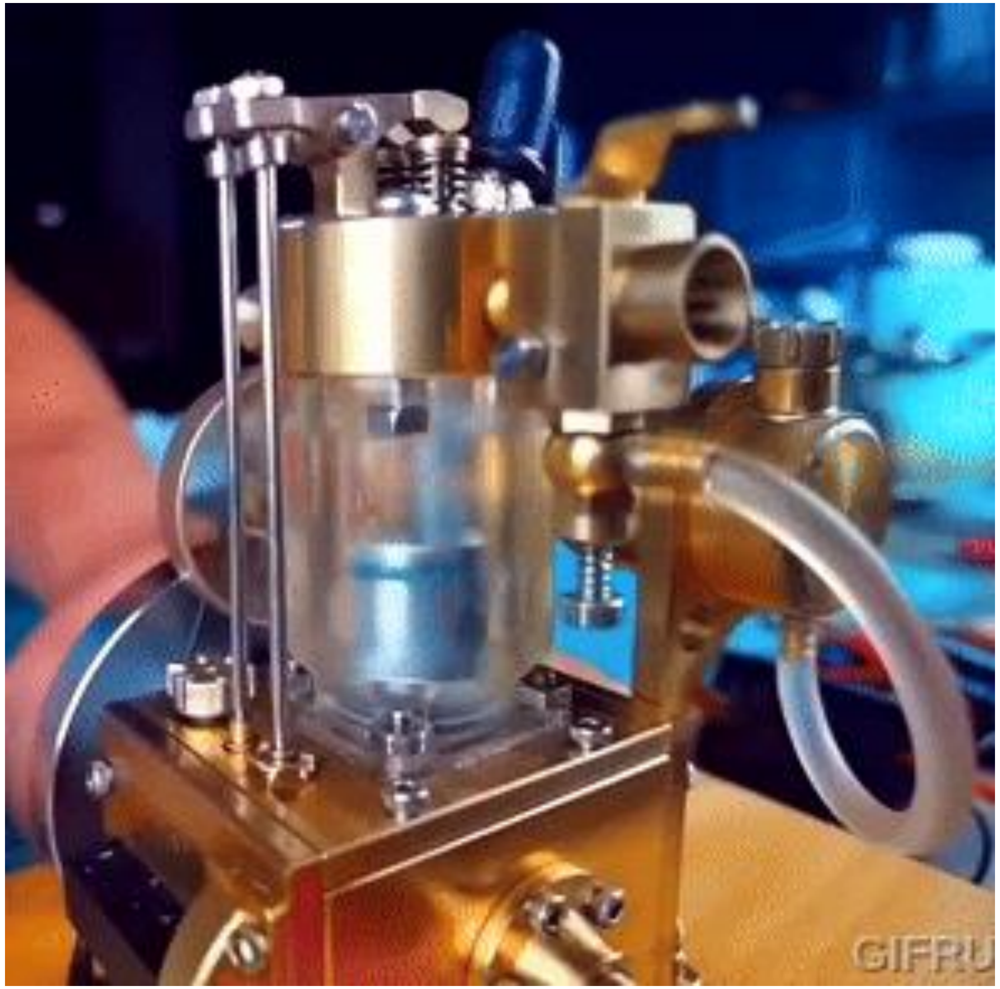
When I compose two systems A and B
The *extensive* properties are *summed*

When I compose two systems A and B
The *intensive* properties are *averaged*

Example: (total) charge ——— density ⟶ Example: (average) charge *density*

What is thermodynamics?

- Thermodynamics studies the conversion between *heat* and *work* - and the relation of these concepts with energy, temperature and entropy



https://youtu.be/cBRo1uH5H6Y?feature=shared

Heat and work – what is work?

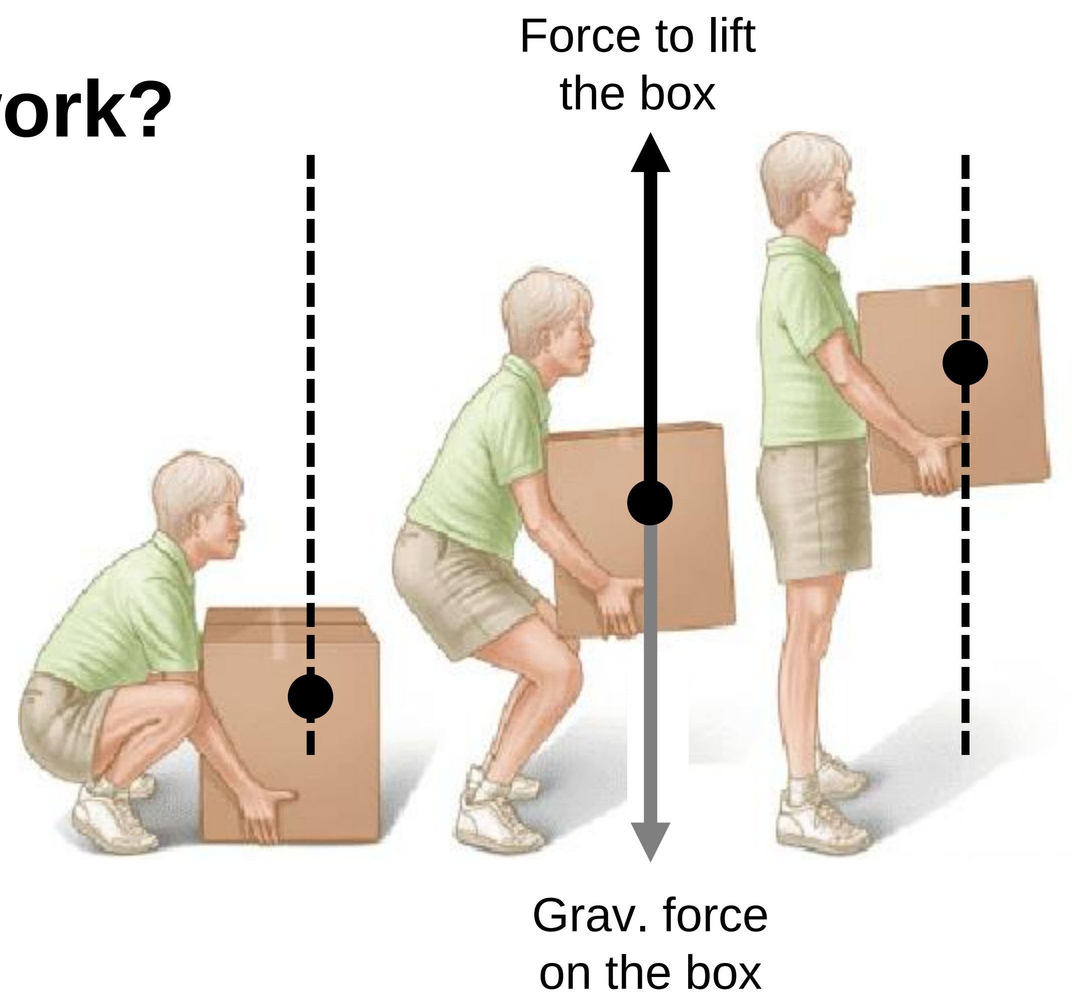
- Work is the product of a force and a displacement.

$$W = F\Delta x$$

- It is has dimensions of energy, so it is measured in joules [J = N m].

- For a variable force, we have to use an integral:

$$W = \int_{x_1}^{x_2} F\, dx$$



Heat and work – what is work?

- Work is the product of a force and a displacement.

$$W = F\Delta x$$

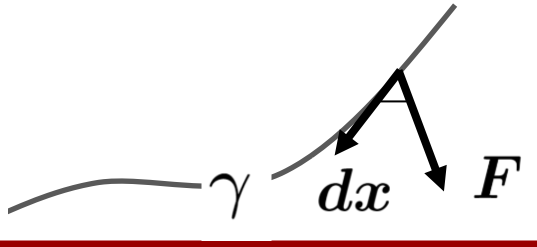
- It is has dimensions of energy, so it is measured in joules [J = N m].

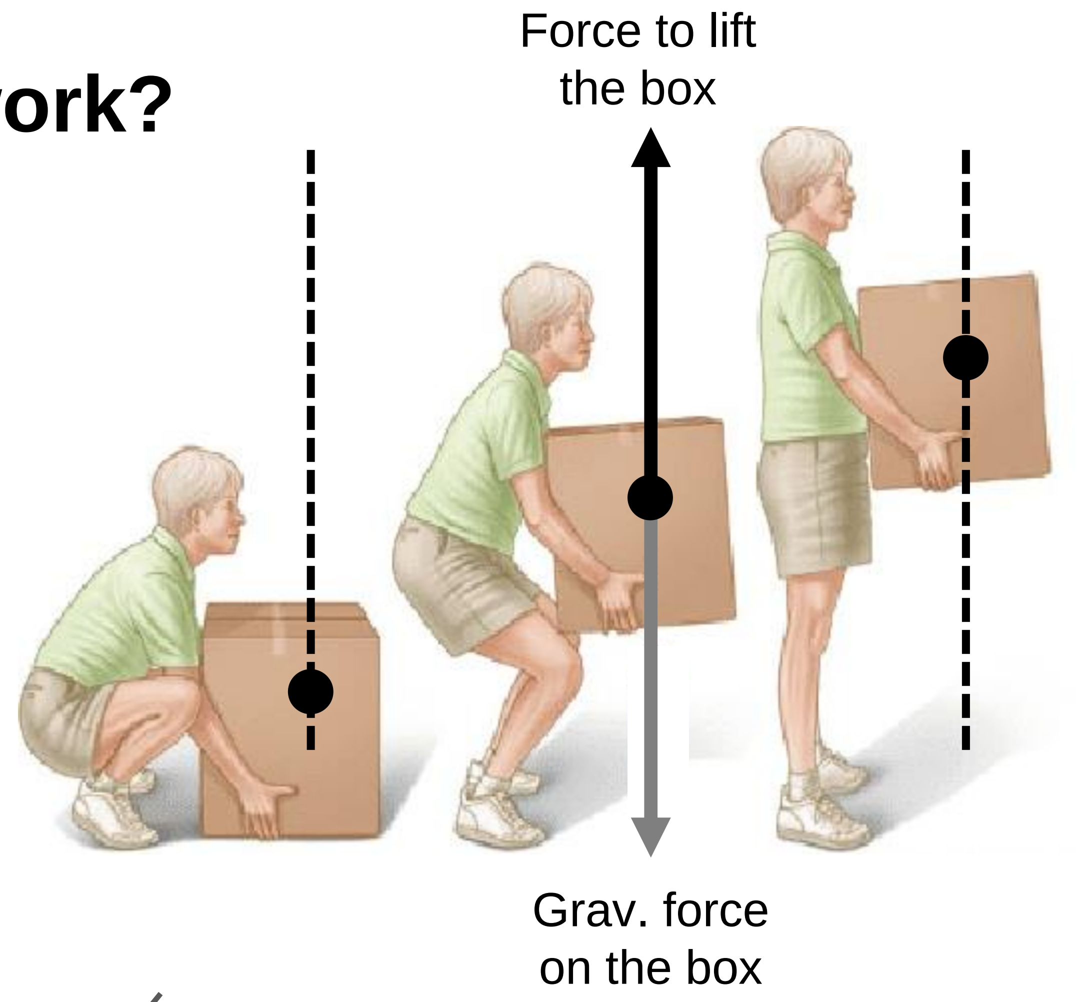
- For a variable force, we have to use an integral:

$$W = \int_{x_1}^{x_2} F\, dx$$

- For 3D situations, we have to take into account the direction:

$$W = \int_{\gamma} \boldsymbol{F} \cdot \boldsymbol{dx}$$





Work and kinetic energy

- Work is the product of a force and a displacement.

$$W = F\Delta x$$

- It is has dimensions of energy, so it is measured in joules [J = N m].

- For a variable force, we have to use an integral:

$$W = \int_{x_1}^{x_2} F\,dx$$

The total force acting on a body is proportional to the acceleration

$$F = ma$$

$$a = \frac{dv}{dt} = \frac{dv}{dx}\frac{dx}{dt} = \frac{dv}{dx}v$$

$$W = m\int_{x_1}^{x_2} a\,dx = m\int_{x_1}^{x_2} \frac{dv}{dx}v\,dx$$

$$= m\int_{v_1}^{v_2} v\,dv = \frac{1}{2}m\left[v^2\right]_{v_1}^{v_2} = \Delta K$$

$$\Rightarrow W = \Delta K$$

Kinetic energy $K = \frac{1}{2}mv^2$

Conservative forces and potential energy

Some forces are conservative, some are not.

It depends on the way the force depends on the position.

(Velocity-dependent forces are never conservative).

Position dependent forces are conservative when the work between two positions does not depend on the path

For conservative forces, we have can define a potential energy difference ΔPE

Conservative forces and potential energy

Some forces are conservative, some are not.

It depends on the way the force depends on the position.

(Velocity-dependent forces are never conservative).

Position dependent forces are conservative when the work between two positions does not depend on the path

For conservative forces, we have can define a potential energy difference ΔPE

In 1D all forces are conservative. The work is:

$$W = \int_{x_1}^{x_2} f(x)\, dx$$

Let's consider two examples

- Gravitational force[§] $f = -mg$

$$W = \int_{x_1}^{x_2} -mg\, dx = -mg\,\Delta x = -\Delta PE$$

- Spring force $f = -kx$

$$W = \int_{x_1}^{x_2} -kx\, dx = -\frac{1}{2}k\Delta x^2 = -\Delta PE$$

§ Note that most commonly, the symbol used for the vertical direction (i.e. the variable appearing in the expression of the gravitational potential energy) is "*z*", and not "*x*".

Conservative forces and potential energy

Some forces are conservative, some are not.

It depends on the way the force depends on the position.

(Velocity-dependent forces are never conservative).

Position dependent forces are conservative when the work between two positions does not depend on the path

For conservative forces, we have can define a potential energy difference ΔPE

In 1D all forces are conservative. The work is:

$$W = \int_{x_1}^{x_2} f(x)\, dx = \boxed{-\Delta PE = \Delta K}$$

Energy conservation

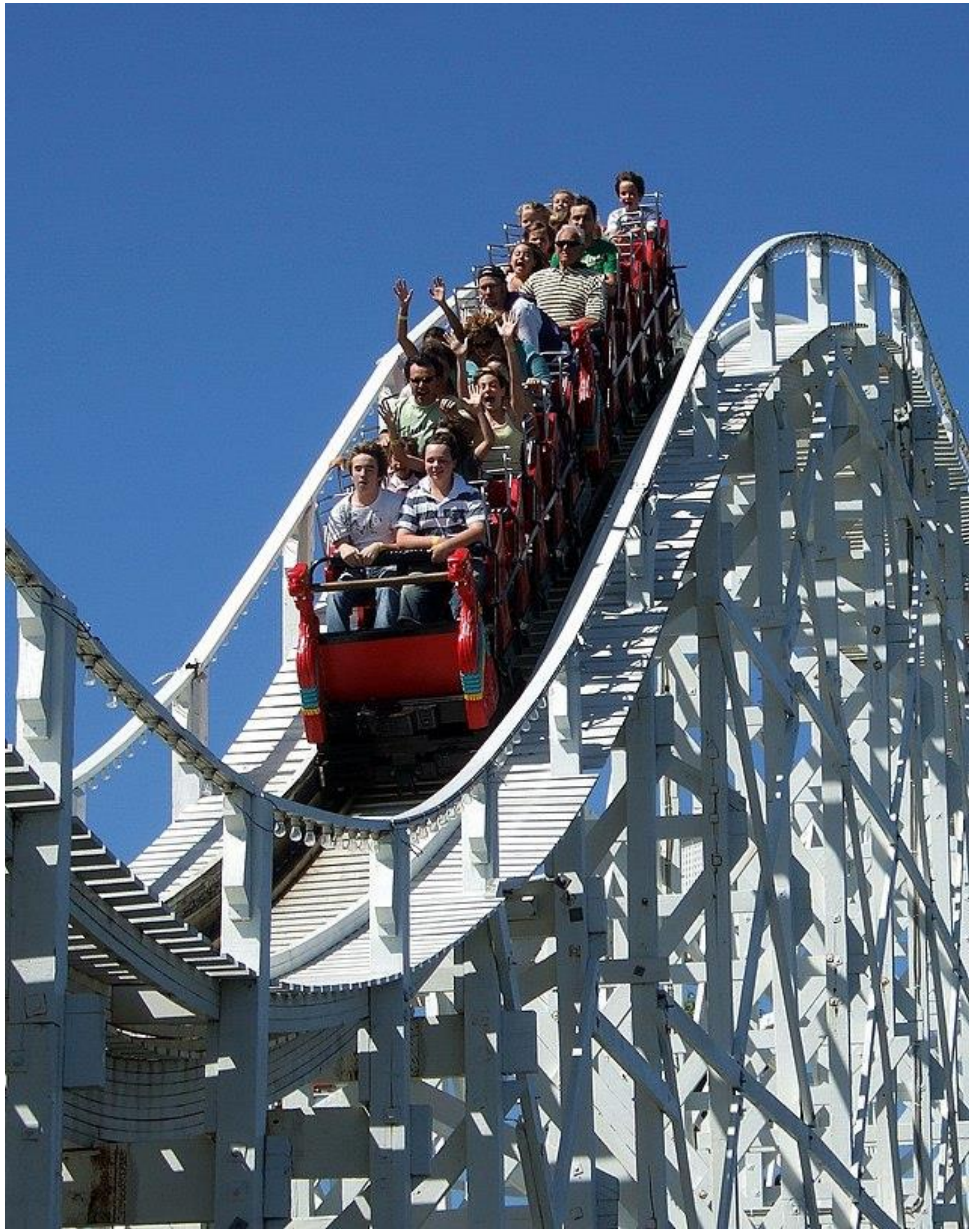
Let's consider two examples

- Gravitational force $f = -mg$

$$W = \int_{x_1}^{x_2} -mg\, dx = -mg\, \Delta x = -\Delta PE$$

- Spring force $f = -kx$

$$W = \int_{x_1}^{x_2} -kx\, dx = -\frac{1}{2} k \Delta x^2 = -\Delta PE$$



kinetic energy

potential energy

In 1D all forces are conservative. The work is:

$$W = \int_{x_1}^{x_2} f(x)\,dx = \boxed{-\Delta PE = \Delta K}$$

Energy conservation

Let's consider two examples

- Gravitational force $f = -mg$

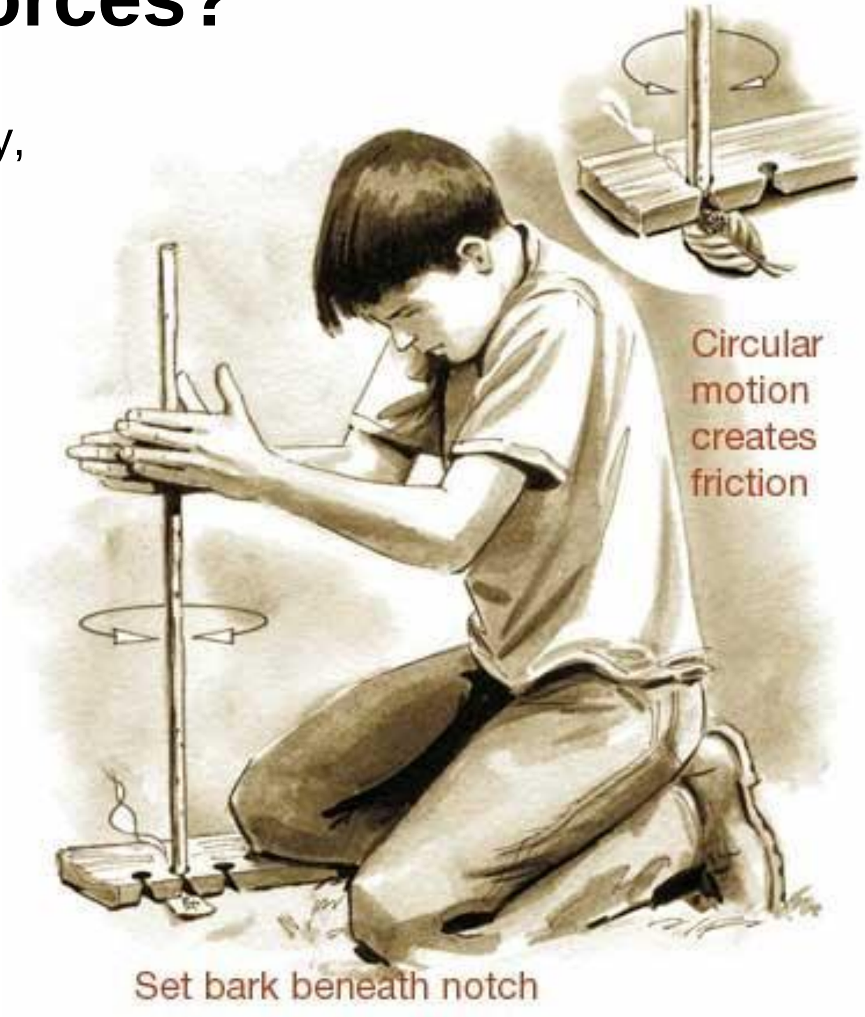
$$W = \int_{x_1}^{x_2} -mg\,dx = -mg\,\Delta x = -\Delta PE$$

- Spring force $f = -kx$

$$W = \int_{x_1}^{x_2} -kx\,dx = -\frac{1}{2}k\Delta x^2 = -\Delta PE$$

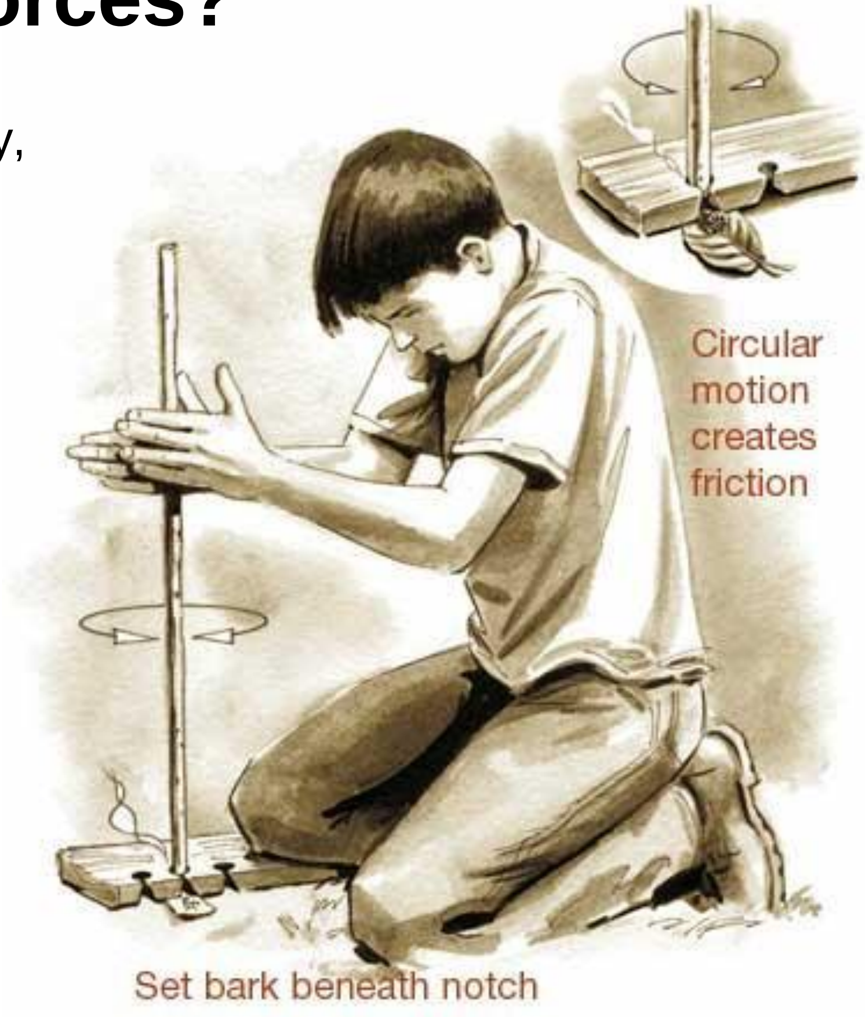
What about non conservative forces?

When a non conservative force is doing work on an body,
it may seem that the energy is disappearing.



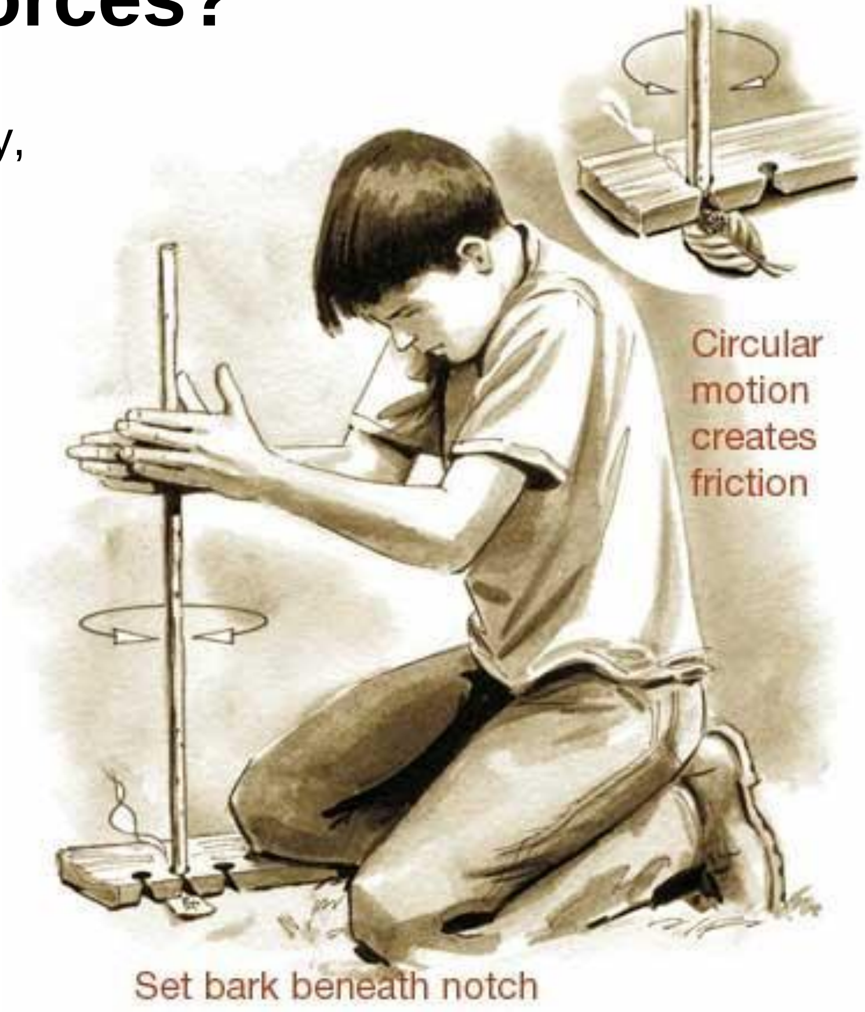
What about non conservative forces?

When a non conservative force is doing work on an body, it may seem that the energy is disappearing.



What about non conservative forces?

When a non conservative force is doing work on an body, it may seem that the energy is disappearing.



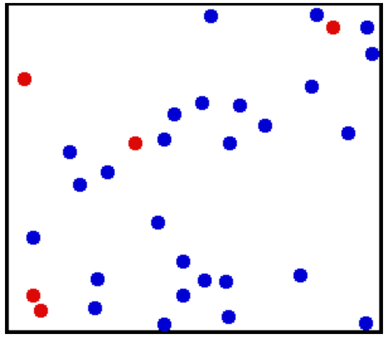
What about non conservative forces?

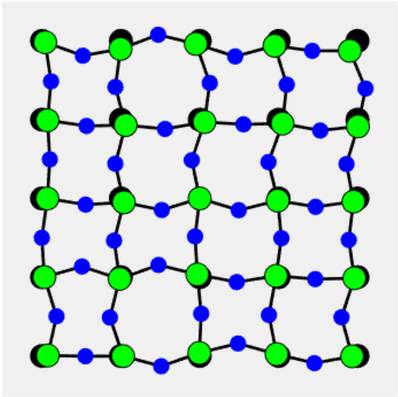
When a non conservative force is doing work on an body,
it may seem that the energy is disappearing.

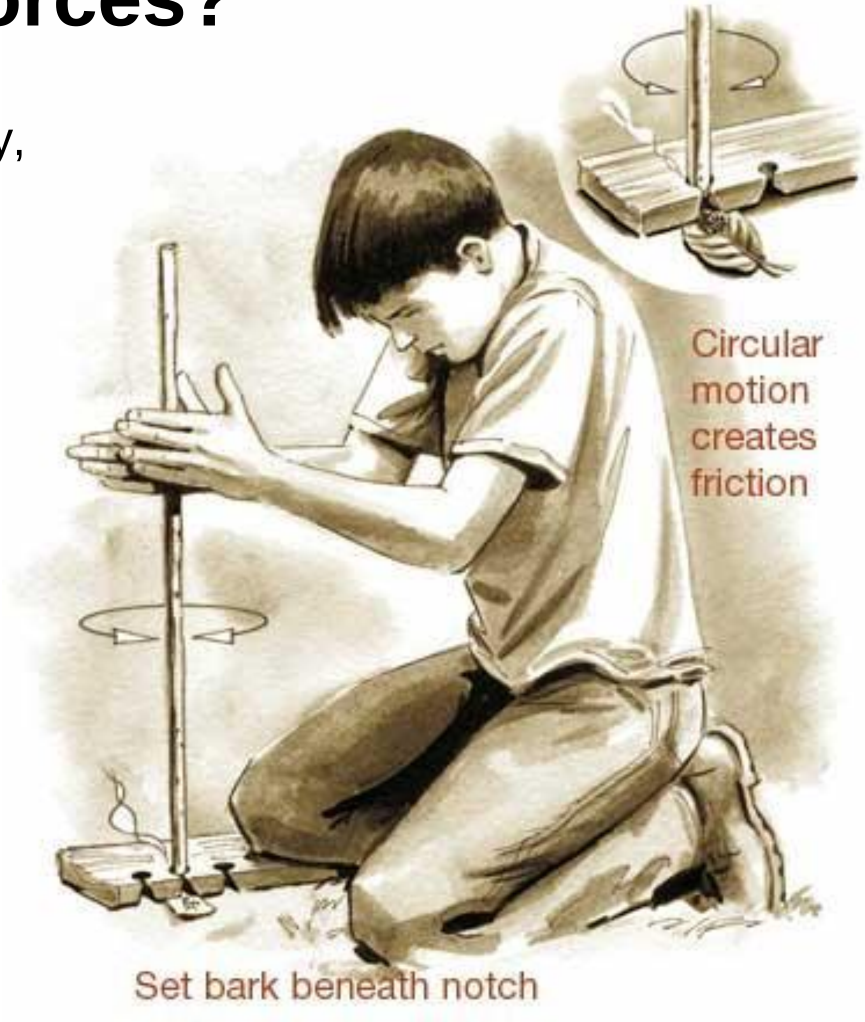
ΔU

It increased the *internal* energy of something

Where did the energy go?







Thermodynamic systems

- It can be anything. Whatever is relevant to our analysis.

- However, very often we concern ourselves with relatively simple cases:
  - A given amount of gas
  - A mixture of a liquid and the vapor of the same substance
  - A solid that can be considered homogeneous

- We define the system by delimiting from the rest of the universe. The boundary between the system and the universe can be
  - a real boundary (the walls of a container) or → matter cannot be exchanged (closed system)
  - an imaginary boundary (a region of space) → matter can be exchanged (open system)

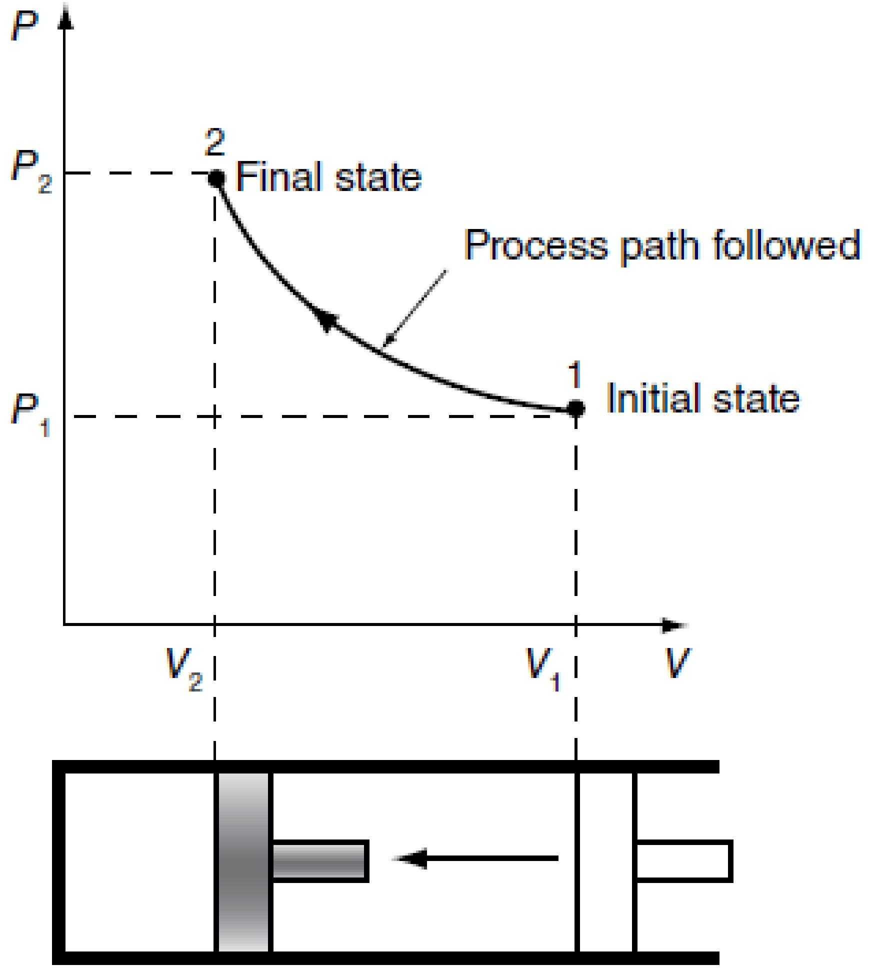
Thermodynamic states

A state is the record of properties for a system.
It can be described by a range of thermodynamic coordinates (properties)

Changing the properties of a system brings it to another state.

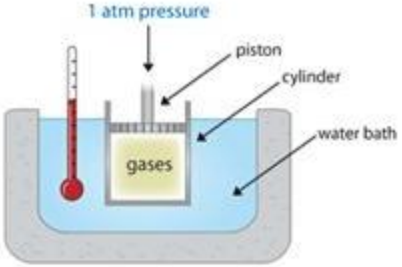
The journey from one state to another is called a *process*.

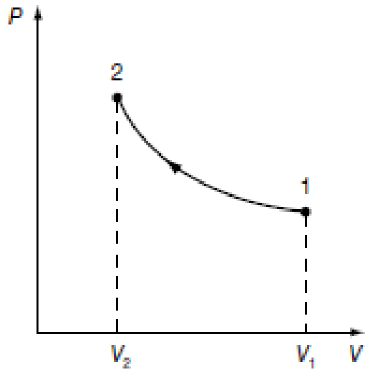
We will mostly concern ourselves with 4 types of processes: isothermal, isochoric, isobaric, adiabatic



Isothermal process

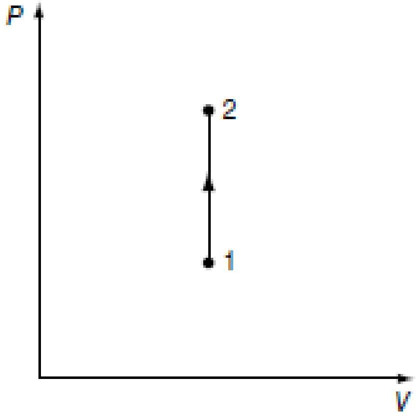
- Constant temperature





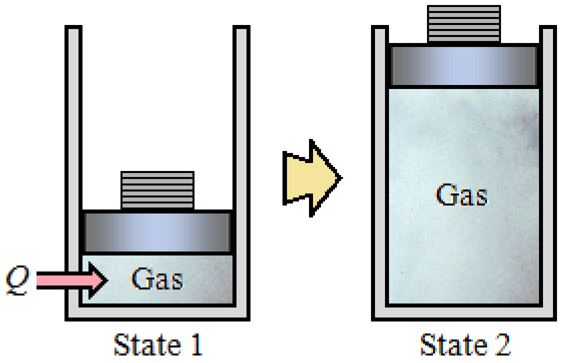
Isochoric process

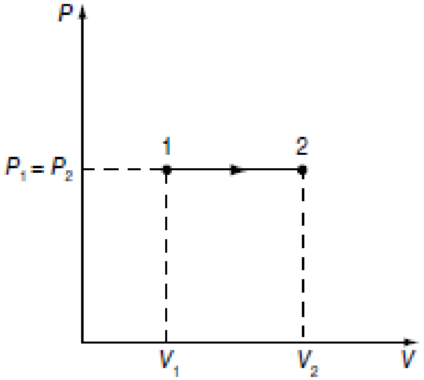
- Constant volume



Isobaric process

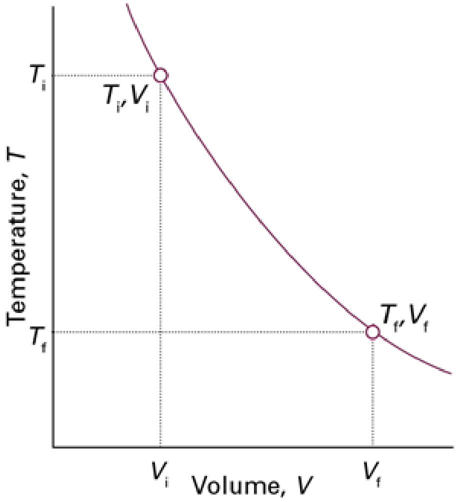
- Constant pressure





Adiabatic process

- <u>No heat exchange</u>



State functions and Path functions

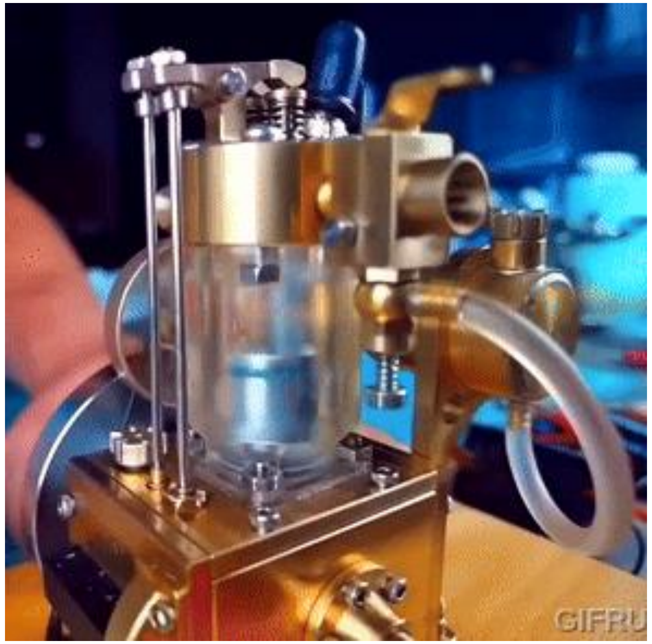
State Function

- Independent of path γ taken to establish property or value
- Can integrate using final and initial values
- Based on established state of system
  - Temperature
  - Pressure
  - Amount of substance

Path Function

- Dependent of path γ taken to establish property or value
- Needs information on function and limits to integrate
- Based on *how* the state of the system was established
  - Heat
  - Work

Cyclic processes



A cycle is a process or series of processes that restore a system to its initial state

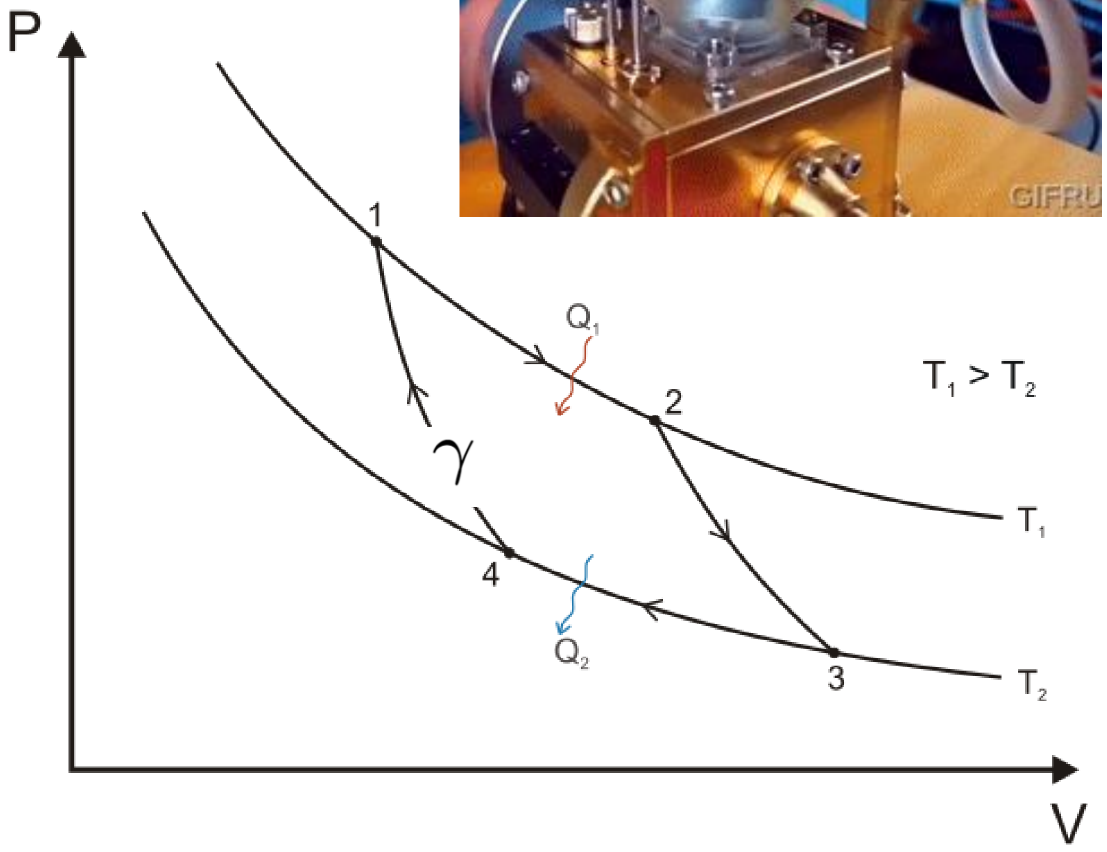
This means that integrating a property over a cycle will always give zero, e.g.
It is true for any state functions!

$$\oint_\gamma dV = 0$$

However, the transfer of energy in the form of heat or work will not be zero.
These are path functions!

$$\oint_\gamma dW = ?$$

All processes that do work *continuously* must be cycles. This makes the analysis of cycles immensely important!



Example problem 2.7

A cylindrical water tank, 3 m high and 3 m in diameter is filled with water. If the density of water is 1000 kg/m3, what is the mass of the contained water? If the acceleration due to gravity is 9.81 m/s^2, what is the weight of the water?

Problem 2.7 - Solution

A cylindrical water tank, 3 m high and 3 m in diameter is filled with water. If the density of water is 1000 kg/m3, what is the mass of the contained water? If the acceleration due to gravity is 9.81 m/s^2, what is the weight of the water?

- The volume of a cylinder is:

$$V_{cyl} = \frac{\pi}{4} D^2\ H = \frac{\pi}{4}(3\ m)^2\ 3\ m = 21.21\ m^3$$

- Then the mass is:

$$m = \rho\ V = 1000 \frac{kg}{m^3} 21.21\ m^3 = 21210\ kg$$

- And the weight is

$$F_w = m\ a = 21210\ kg\ 9.81 \frac{m}{s^2} = 208{,}030\ N$$

Exercises chapter 2

- 2.5
- 2.8
- 2.12
- 2.27
- 2.28