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Thermodynamics

Module 1 Fundamental Concepts

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- Definition of thermodynamics
- Systems of units
- Systems and control volumes
- Properties of a system
- States and equilibrium
- Processes and cycles
- Laws of thermodynamics
- Temperature and pressure

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Definition of thermodynamics

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Definition of thermodynamics

Science that studies energy, heat and work; as well as the thermophysical properties of the substances involved in energy transformation processes.

Energy, heat and work

Heat

It is what the system
DELIVERS or RECEIVES

Energy

It is what the system
POSSESSES

Work

It is what the system
DELIVERS or RECEIVES

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Energy, heat and work

What is a system?



Energy, heat and work

How can I change the energy of a system?

Heat

by putting it in contact with something at a different temperature

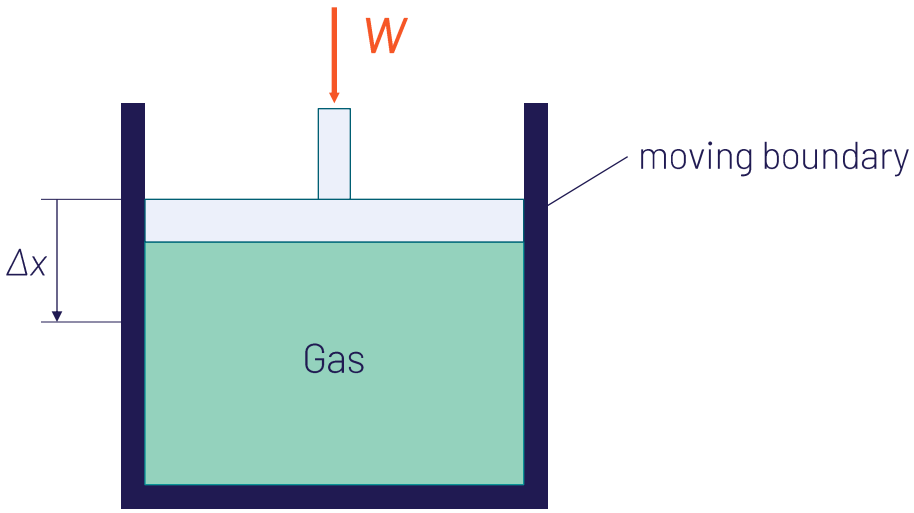
Work

by exerting a force that displaces or deforms it

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Energy, heat and work

What do I have to do to a system if I want it to change through Work?

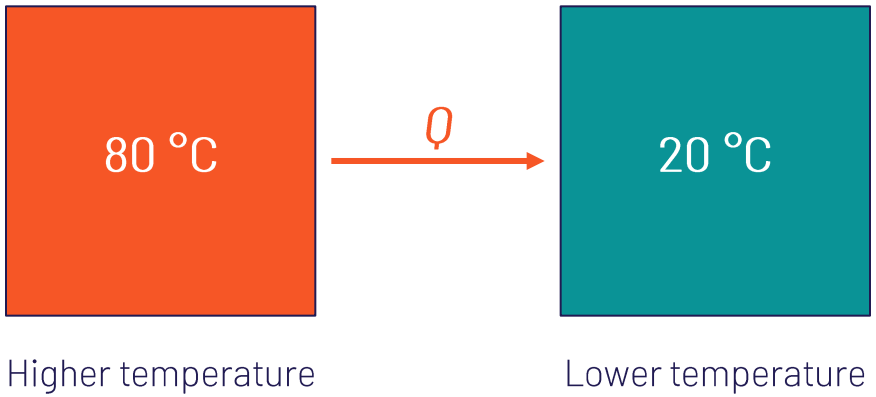


Exert a force
that displaces or deforms it

Compress it, expand it, stir it, spin it, pass current through it

Energy, heat and work

What do I have to do to a system if I want it to change through Heat?



Put it in contact
with something at a different temperature

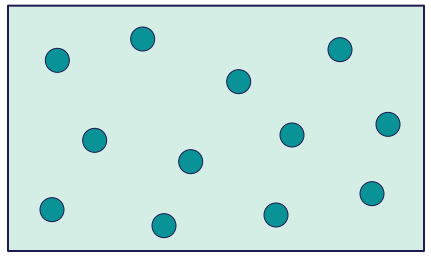
Without a temperature difference there is no heat transfer

Heat always flows from the body at higher temperature to the one at lower temperature, never the other way around on its own.

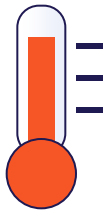
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Classification of thermodynamics

Microscopic or Statistical Thermodynamics



molecule by molecule



Instrument

Macroscopic or Classical Thermodynamics

One studies molecule by molecule. The other measures the whole with an instrument.

In this course we work with the macroscopic approach.

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Before we continue...

What is the difference between the energy a system possesses and heat?

Energy is possessed; heat only exists while it crosses the boundary.

You rub your hands on a cold day and they warm up. Was it heat or work?

Work. There was force and displacement, not contact with something hotter.

Why does it make no sense to say that a body contains a lot of heat?

Because heat is not stored. What is stored is energy.

If you measure the temperature of a gas with a thermometer, which approach are you using?

The macroscopic one. You do not need to know anything about the molecules one by one.

Food for thought

I run a blender with water inside, with the jar covered and insulated. After a while the water is hotter.

Answer yes or no for each one

Heat entered the water No	Work entered Yes, from the motor
Its energy increased Yes	Its temperature increased Yes

So, did the water heat up without receiving heat?

The key

Yes. The jar is insulated, so there was no heat transfer. The energy entered as work from the blades.

Heat and work are different paths to the same destination: changing the energy.

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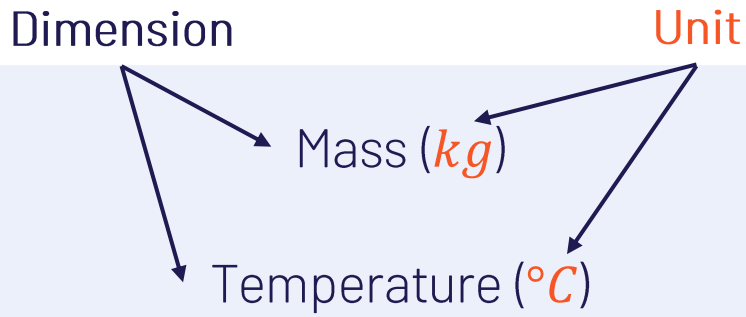
Systems of units



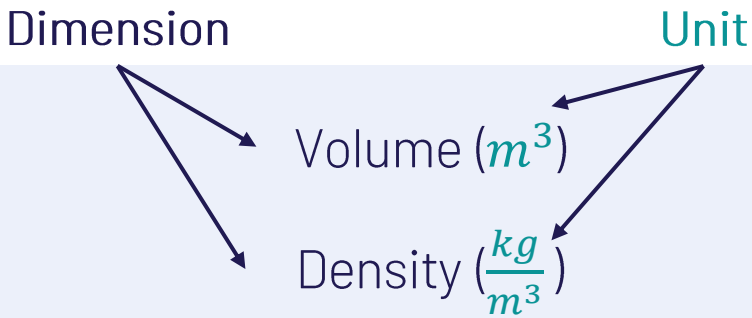
Systems of units

A dimension is the measurable physical property of a system (such as length or temperature) and a unit is the arbitrary standard value we use to quantify it (such as the meter or the kelvin).

Primary Dimensions



Secondary Dimensions



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Systems of units

DIMENSION	SYMBOL	UNIT
Mass	M	kg (lbm)
Length	L	m (ft)
Temperature	T	K (R)

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Systems of units

DIMENSIÓN	MÉTRICO	MÉTRICO/INGLÉS
Aceleración	1 m/s^2 = 100 cm/s^2	1 m/s^2 = 3.2808 ft/s^2 1 ft/s^2 = 0.3048* m/s^2
Área	1 m^2 = 10^4 cm^2 = 10^6 mm^2 = 10^{-6} km^2	1 m^2 = 1 550 in^2 = 10.764 ft^2 1 ft^2 = 144 in^2 = 0.09290304* m^2
Densidad	1 g/cm^3 = 1 kg/L = 1 000 kg/m^3	1 g/cm^3 = 62.428 lbm/ft^3 = 0.036127 lbm/in^3 1 lbm/in^3 = 1 728 lbm/ft^3 1 kg/m^3 = 0.062428 lbm/ft^3
Energía, calor, trabajo, energía interna, entalpía	1 kJ = 1 000 J = 1 000 N · m = 1 kPa · m^3 1 kJ/kg = 1 000 m^2/s^2 1 kWh = 3 600 kJ 1 cal† = 4.184 J 1 IT cal† = 4.1868 J 1 Cal† = 4.1868 kJ	1 kJ = 0.94782 Btu 1 Btu = 1.055056 kJ = 5.40395 psia · ft^3 = 778.169 lbf · ft 1 Btu/lbm = 25 037 ft^2/s^2 = 2.326* kJ/kg 1 kJ/kg = 0.430 Btu/lbm 1 kWh = 3 412.14 Btu 1 termia = 10^5 Btu = 1.055 × 10^5 kJ (gas natural)
Fuerza	1 N = 1 kg · m/s^2 = 10^5 dina 1 kgf = 9.80665 N	1 N = 0.22481 lbf 1 lbf = 32.174 lbm · ft/s^2 = 4.44822 N
Flujo de calor	1 W/cm^2 = 10^4 W/m^2	1 W/m^2 = 0.3171 Btu/h · ft^2
Coeficiente de transferencia de calor	1 W/m^2 · °C = 1 W/m^2 · K	1 W/m^2 · °C = 0.17612 Btu/h · ft^2 · °F
Longitud	1 m = 100 cm = 1 000 mm = 10^6 μm 1 km = 1 000 m	1 m = 39.370 in = 3.2808 ft = 1.0926 yd 1 ft = 12 in = 0.3048* m 1 milla = 5 280 ft = 1.6093 km 1 in = 2.54* cm

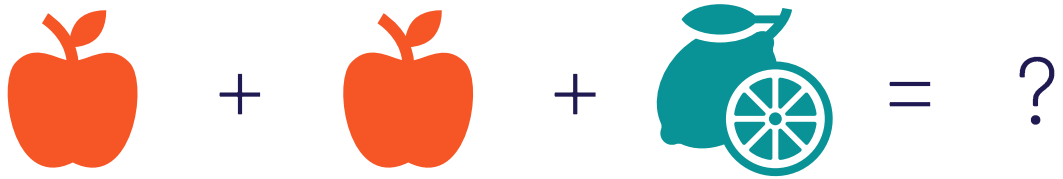
TABLA 1-2

Prefijos estándar en unidades SI

Múltiplos	Prefijo
10^{24}	yotta, Y
10^{21}	zetta, Z
10^{18}	exa, E
10^{15}	peta, P
10^{12}	tera, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deca, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	mili, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p
10^{-15}	femto, f
10^{-18}	atto, a
10^{-21}	zepto, z
10^{-24}	yocto, y

Dimensional homogeneity

Each term in an equation must have the same unit



Dimensional homogeneity

Verify dimensional homogeneity

$$\boxed{\frac{P}{\rho g}} + \boxed{\frac{V^2}{2g}} + \boxed{gz} =$$

$$\boxed{\frac{P}{\rho g}} + \boxed{} + \boxed{} =$$

$$\frac{\frac{N}{m^2}}{\frac{kg}{m^3}\frac{m}{s^2}} = \frac{\frac{kg\ m}{s^2}}{\frac{kg}{m^3}\frac{m}{s^2}} = m$$



$$\boxed{} + \boxed{\frac{V^2}{2g}} + \boxed{} =$$

$$\frac{\frac{m^2}{s^2}}{\frac{m}{s^2}} = m$$



$$\boxed{} + \boxed{} + \boxed{gz} =$$

$$\frac{m}{s^2}\, m = \frac{m^2}{s^2}$$



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Dimensional homogeneity

Verify dimensional homogeneity

$$\boxed{\frac{P}{\rho g}} + \boxed{\frac{V^2}{2g}} + \boxed{z} =$$

$$\boxed{\frac{P}{\rho g}} + \boxed{\quad} + \boxed{\quad} = \frac{\frac{N}{m^2}}{\frac{kg}{m^3}\frac{m}{s^2}} = \frac{\frac{kg\ m}{s^2}}{\frac{kg}{m^3}\frac{m}{s^2}} = m$$

$$\boxed{\quad} + \boxed{\frac{V^2}{2g}} + \boxed{\quad} = \frac{\frac{m^2}{s^2}}{\frac{m}{s^2}} = m$$

$$\boxed{\quad} + \boxed{\quad} + \boxed{z} = m$$

Dimensional homogeneity

Verify dimensional homogeneity

$$\frac{1}{2}\rho v^2 \longrightarrow ?$$

$$\frac{1}{2}\rho v^2 \longrightarrow \left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right)\cdot\left(\frac{\mathrm{m}^2}{\mathrm{s}^2}\right) = \frac{\mathrm{N}}{\mathrm{m}^2} = \mathrm{Pa}$$

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Exercise

The power delivered by a pump is calculated with

$$\dot{W} = \rho g Q h$$

Data: $\rho = 1000\ kg/m^3$ $g = 9.81\ m/s^2$ $Q = 0.05\ m^3/s$ $h = 12\ m$

a) Verify that the equation is dimensionally homogeneous

b) Calculate the power in kilowatts

Try part a) without a calculator: using units only.

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Solution

a) I substitute units on the right-hand side

$$\frac{kg}{m^3} \cdot \frac{m}{s^2} \cdot \frac{m^3}{s} \cdot m = \frac{kg \cdot m^2}{s^3} = W$$

It ends up in watts, which is a unit of power: the equation is homogeneous.

b) I substitute the values

$$\dot{W} = 1000 \cdot 9.81 \cdot 0.05 \cdot 12 = 5886\ W$$

$$\dot{W} = 5.89\ kW$$

If part a) had not given watts, part b) would not be worth the trouble.

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Before we continue...

What is the difference between a dimension and a unit?

A dimension is the property being measured; the unit is the standard used to quantify it.

Is density a primary or a secondary dimension?

Secondary. It is built by combining mass and length.

What does dimensional homogeneity require in an equation?

That all terms added or set equal have the same units.

When checking units you end up with kg/m^3 where you expected pressure. What does that mean?

That the equation is set up incorrectly. Homogeneity is the first filter.

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Food for thought

A classmate gives you this formula to calculate the pressure at the bottom of a tank:

$$P = \rho g h^2$$

Do you accept it or reject it, and why?

The key

It is rejected. When units are substituted, the right-hand side ends up in newtons per meter, not newtons per square meter.

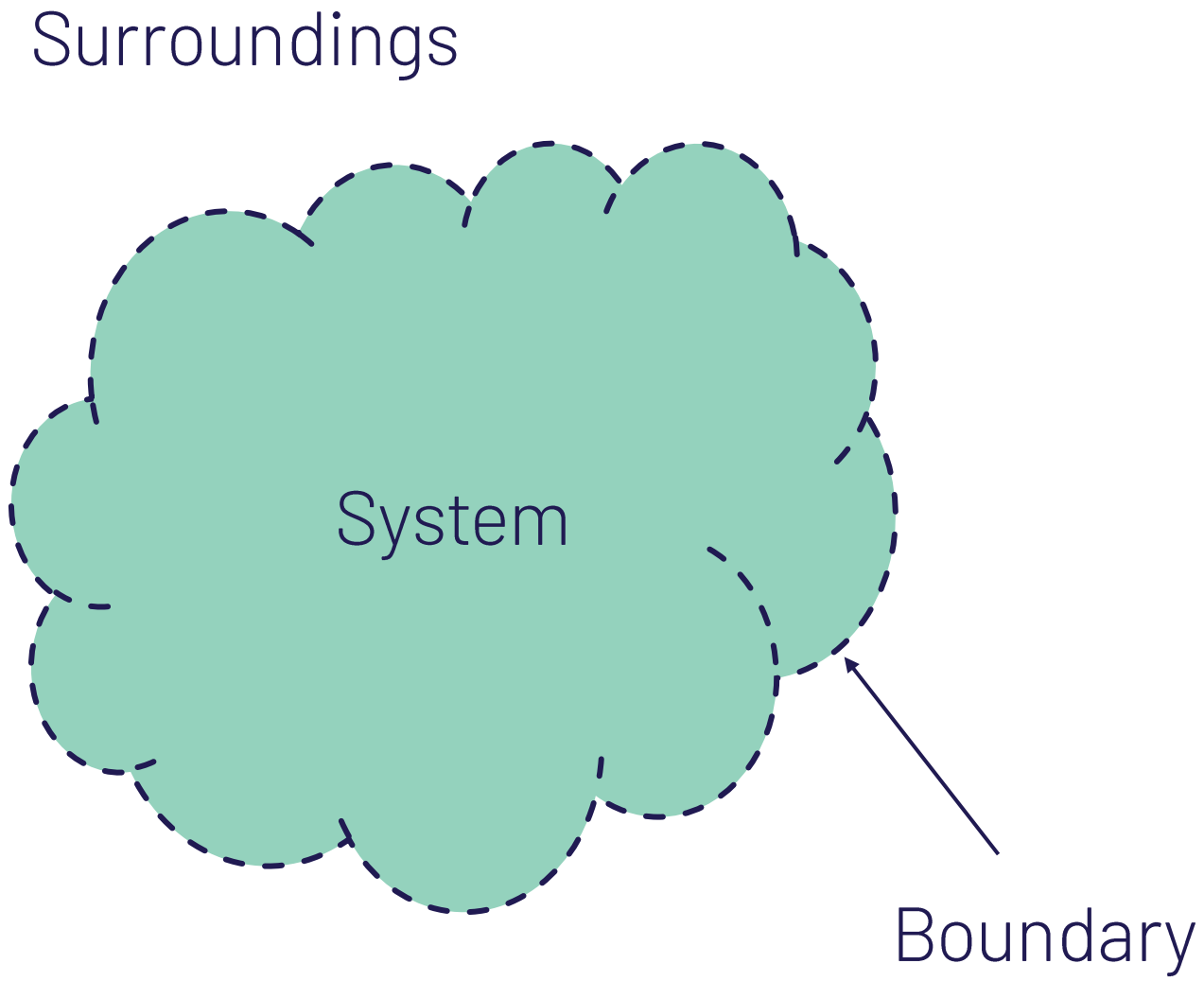
There is an extra power of the height. Dimensional homogeneity reveals it on its own.

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Systems and control volumes

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Definitions



Key concepts

System

Quantity of matter or region in space chosen for analysis.

Surroundings

Mass or region outside the system.

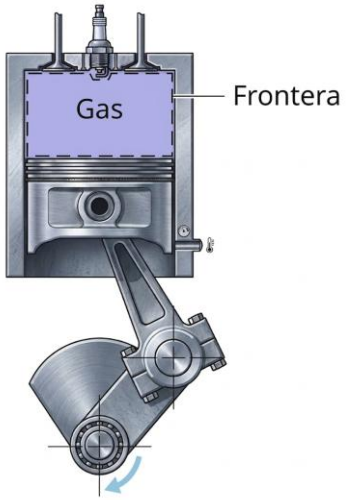
Boundary

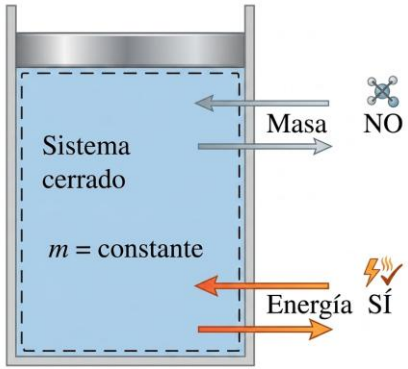
Surface (real or imaginary) that separates the system from its surroundings. It can be fixed or moving.

Closed Systems
(control mass)

Consists of a fixed amount of mass, and no other mass can cross its boundaries.

Mass cannot cross the boundary, but energy can

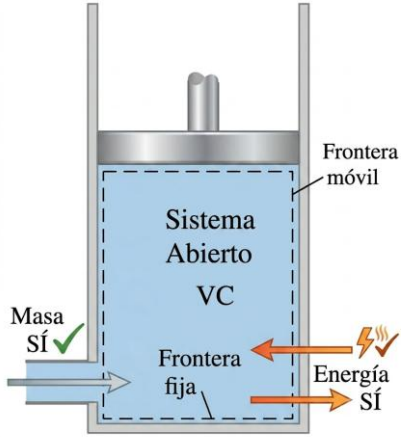


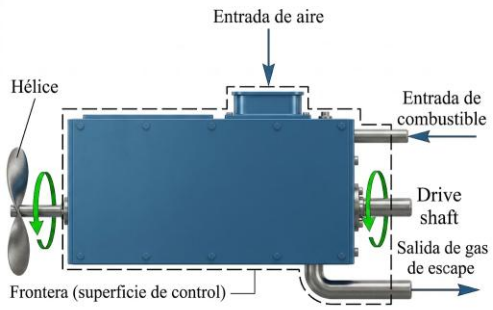


Open Systems
(control volume)

A properly chosen region in space, usually enclosing a device through which mass flows.

Mass can cross the boundary and energy can





Before we continue...

What decides whether something is the system or the surroundings?

You do. You choose the region you want to analyze and everything else becomes the surroundings.

Does the boundary of a system have to be a real wall?

No. It can be imaginary, and it can also move, like the face of a piston.

In a closed system, what can cross the boundary and what cannot?

Energy does cross, mass does not.

An uncovered pot of boiling water: closed or open?

Open. Steam is leaving, that is, mass.

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Food for thought

A pressure cooker on the stove. First sealed, and after a while it starts releasing steam through the valve.

Classify each moment

Sealed, heating up Closed system	Releasing steam Control volume
Does energy enter? Yes, always	Does the boundary move? No, the cooker is rigid

Did the same device change category halfway through?

The key

Yes, and that is normal. While nothing leaves, it is best analyzed as a fixed mass. Once steam starts leaving, mass is crossing.

The classification is not of the device: it is of how you decide to analyze it.

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Properties of a system



Properties of a system

I give you this potato. What can you measure about it?



Mass, volume, temperature, color, hardness, moisture, speed, height...

All of those are properties

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Properties of a system

What is a property?

Any characteristic of a system

P	T	V	m
pressure	temperature	volume	mass

If I can measure or calculate it in the system, it is a property.

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Properties of a system

But not all of them are so obvious...

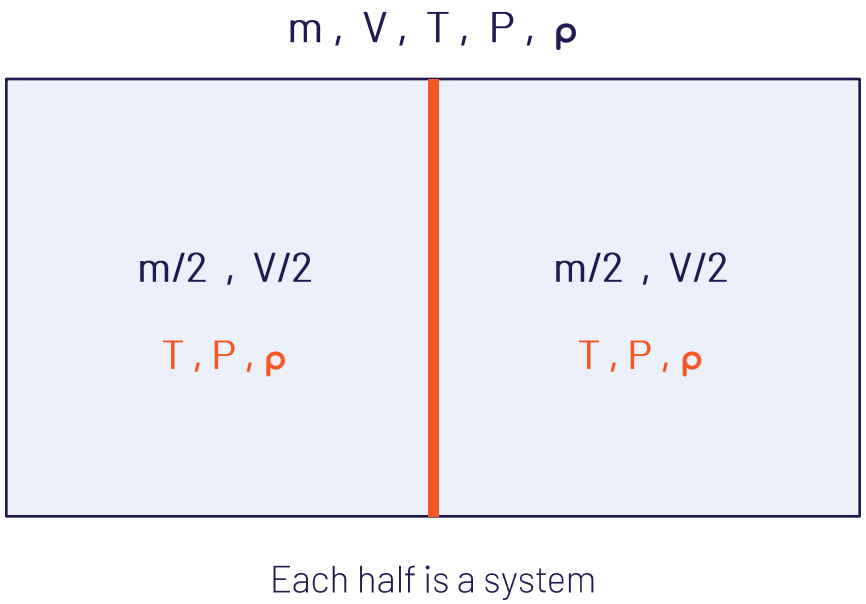
Viscosity	Thermal conductivity	Modulus of elasticity	Coefficient of thermal expansion
Electrical resistivity	Velocity	Elevation	Internal energy

They all describe the state of the system at a given instant.

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Properties of a system

If I divide the system into two equal halves... what happens to each property?



m y V

they are halved

T, P y ρ

they stay the same

Properties of a system

Intensive

Are independent of the mass of the system

$T,$ $P,$ $\rho,$ v

Extensive

Depend on the size or extent of the system

$m,$ $V,$ E

If I split the system in half… which ones are halved?

Only the extensive ones. The intensive ones do not change.

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Properties of a system

How do I tell them apart just by seeing them written?

Extensive
UPPERCASE
$V,$ $E,$ $U,$ H

Specific
lowercase
$v,$ $e,$ $u,$ h

The exceptions you have to memorize:

m mass is extensive and is written in lowercase
$T,$ P are intensive and are written in uppercase

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Specific properties

What if I want to compare two systems of different sizes?

I divide the extensive property by the mass and it becomes intensive

Specific volume

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

m^3/kg

Specific total energy

$$e = \frac{E}{m}$$

kJ/kg

So 2 kg and 200 kg of the same substance in the same state have the same specific volume.

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Quick check

Classify each one: intensive or extensive?

$$T \quad m \quad \rho \quad V \quad v \quad P$$

Intensive

$T,$ $\rho,$ $v,$ P

Extensive

$m,$ V

Note: V is extensive, but $v = \frac{V}{m}$ is intensive.

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Density

I have two containers of $1\ m^3$: one full of air and the other full of water.
How much mass does each one contain?

Data: $\rho_{aire} = 1.2\ kg/m^3$ $\rho_{agua} = 1000\ kg/m^3$

Air

$$m = 1.2\ kg$$

Water

$$m = 1000\ kg$$

Same volume, 833 times more mass.

What makes them different is density.

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Density and specific volume

Density = mass per unit volume

Density

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

kg/m^3

Specific volume

$$v = \frac{V}{m} = \frac{1}{\rho}$$

m^3/kg

What if instead of mass I use the number of moles?

I get the molar density and the molar volume

$kmol/m^3$ $m^3/kmol$

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Properties of a system

A tank contains $3\ kg$ of air in a volume of $12\ m^3$.

What is its density and its specific volume?

$$\rho = \frac{m}{V} = \frac{3\ kg}{12\ m^3} = 0.25\ kg/m^3$$

$$v = \frac{V}{m} = \frac{1}{\rho} = 4\ m^3/kg$$

Density and specific volume are reciprocals: one can be obtained from the other.

Solids and liquids

If I squeeze a liter of water with all my strength, does its volume change?

Practically nothing

That is why we treat them as incompressible substances.

Incompressible

A substance whose volume, and therefore its density, barely changes no matter how much the pressure on it is increased.

In practice:
ρ does not depend on P

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Solids and liquids

So, does a liquid's density never change?

T (°C)	ρ (kg/m^3)
0	999.8
20	998.0
40	992.1
50	988.1
75	974.9
100	957.9

Not with pressure,
but yes with temperature

Water goes from $1000\ kg/m^3$ to $988\ kg/m^3$
when heated from 0 to 50 °C

That is why in a liquid we look up ρ in the table according to temperature.

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Gases

And a gas's density, what does it depend on?

On pressure and temperature

$$P = \rho RT \longrightarrow \rho = \frac{P}{RT}$$

R is the specific gas constant of each gas.
For air it is $0.287\ kJ/kg \cdot K$

Ideal gas

A model that assumes molecules are far apart, with no attractive forces between them and with negligible volume.

It works well at
low pressure and high temperature

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Ideal gas and real gas

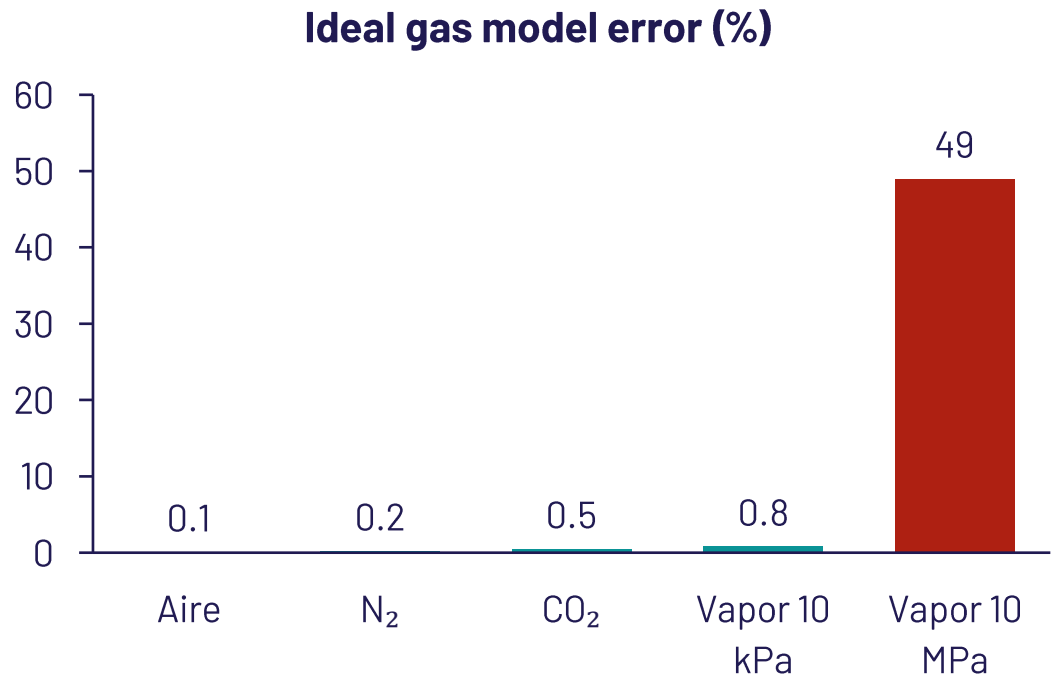
And when does that equation stop working for me?

Ideal gas

It is an idealization: molecules neither attract each other nor occupy volume

Real gas

They do attract each other and do occupy volume; near condensation, the equation fails



Air, nitrogen or oxygen at ambient conditions: error less than 1%.

Water vapor in a boiler: the error is enormous, tables must be used.

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Exercise

A container of $1\ m^3$ is full of air. Then I fill it with water.

How much mass is there in each case and how much does it weigh?

Air $\rho = 1.2\ kg/m^3$

$$m = \rho V = 1.2 \cdot 1 = 1.2\ kg$$

$$W = mg = 1.2 \cdot 9.81$$

$$W = 11.8\ N$$

Water $\rho = 1000\ kg/m^3$

$$m = \rho V = 1000 \cdot 1 = 1000\ kg$$

$$W = mg = 1000 \cdot 9.81$$

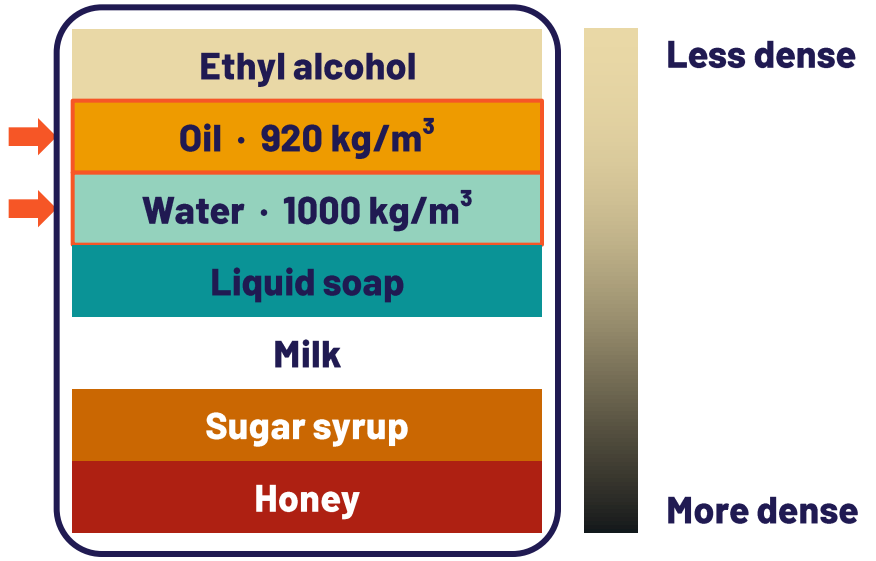
$$W = 9810\ N$$

One ton of water versus a little more than a kilogram of air, in the same volume.

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Specific gravity

Why does oil always stay above water?



Oil floats because it is less dense than water

Because it is less dense

oil ≈ 920 kg/m^3

We compare it against water

water = 1000 kg/m^3

Comparing against water is so useful that it has its own name.

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Specific gravity

The density of a substance compared with that of water

$$SG = \frac{\rho}{\rho_{H_2O}}$$

With the density of water equal to $1000\ kg/m^3$ at 4 °C. Dividing equal units, the result is dimensionless

$SG < 1$	$SG > 1$
floats on water	sinks in water

Oil	Ice	Aluminum	Mercury
0.92	0.92	2.7	13.6

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Specific weight

The weight of a substance per unit volume

$$\gamma = \rho g$$

is measured in N/m^3

Calculate the specific weight of water at 50 °C

First I look up the density of water at 50 °C in the table: $\rho = 988\ kg/m^3$

$$\gamma = 988 \cdot 9.81 = 9693\ N/m^3$$

The routine is always the same: I look up ρ in the table and multiply by g.

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Exercise

A 0.5 m^3 tank is completely filled with 400 kg of a lubricating oil.

Data: $V = 0.5\ m^3$ $m = 400\ kg$ $\rho_{H_2O} = 1000\ kg/m^3$ $g = 9.81\ m/s^2$

Calculate, in this order:

a) its density

b) its specific volume

c) its specific gravity

d) its specific weight

Each result feeds the next: there is no need to go back to the data.

Solution

a) Density

$$\rho = \frac{m}{V} = \frac{400}{0.5} = 800\ kg/m^3$$

b) Specific volume

$$v = \frac{1}{\rho} = \frac{1}{800} = 0.00125\ m^3/kg$$

c) Specific gravity

$$SG = \frac{\rho}{\rho_{H_2O}} = \frac{800}{1000} = 0.8$$

d) Specific weight

$$\gamma = \rho g = 800 \cdot 9.81 = 7848\ N/m^3$$

With SG = 0.8 the oil floats on water, which is exactly what one would expect.

Before we continue...

Two tanks with the same gas, at the same temperature and pressure, but one twice the size. What makes them different?

Only the extensive ones: $m, V\ y\ E$. All the intensive ones are identical.

Can an extensive property become intensive?

Yes, by dividing it by the mass. That is how $v, e, u\ y\ h$ arise.

When heating water in a pot, the hot water rises. Which property explains that?

Density: as T increases, ρ decreases and that fluid rises.

Why is temperature enough for a liquid to find its density, but not for a gas?

The liquid is incompressible, pressure barely affects it. The gas does depend on P.

Now a case where the mass does not change, but everything else does.

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Food for thought

A diver fills a balloon with air at the surface, ties it tightly and takes it down to a depth of 30 m.

What happens to each property of the air inside?

Mass Does not change	Volume Decreases
Density Increases	Specific vol. Decreases

So, is air incompressible?

The key

The balloon is closed: no mass enters or leaves. But the water pressure compresses it, so the same air occupies less volume.

No. Air is a gas: its density depends strongly on pressure.

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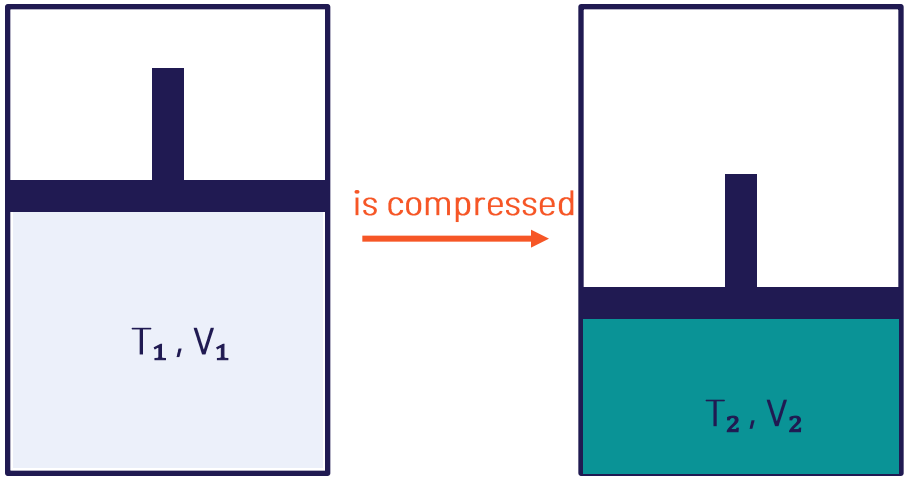
States and equilibrium

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States and equilibrium

The same gas inside the same cylinder, at two different moments.

Is it still the same system?



Yes, the system is the same

the mass did not change

What changed was its

state

What changed were T and V, and with them the whole description of the system.

States and equilibrium

How do I describe the exact condition a system is in?

By listing its properties
and we call that set the state

If I know T, P, v and the others, I know exactly what condition the system is in.

State

Set of properties that completely defines the condition of a system at a given instant.

If no property changes, the state is the same.

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States and equilibrium

If the properties keep changing while I am measuring them, which value do I write down?

None that is reliable

that is why we only study equilibrium states

Classical thermodynamics describes the system before and after the change, not during.

Equilibrium

A state of balance: within the system there is no remaining imbalance forcing it to keep changing.

And there are four different kinds of equilibrium.

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The four equilibria

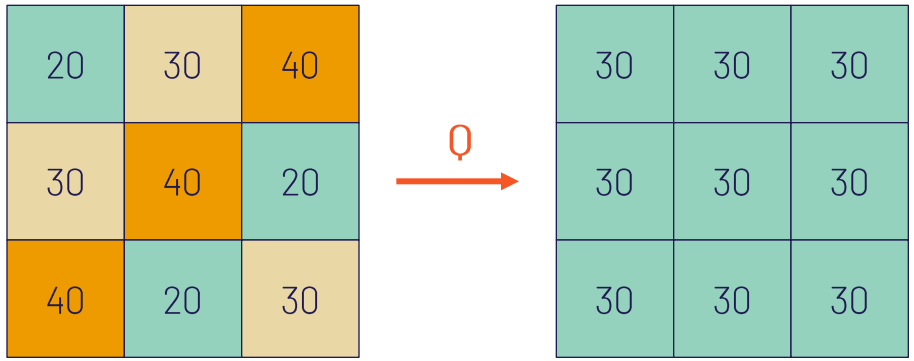
The first two

Thermal

The temperature is the same throughout the system. There are no points hotter than others.

Mechanical

The pressure does not change with time at any point in the system.



The block evens out until it is all at the same temperature

Careful with the mechanical one: we mean that P does not change over time, not that it is the same at every height.

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The four equilibria

And the two that appear when there is more than one phase or a reaction

Phase

When two phases coexist, the mass of each one stops changing and stays there.

Chemical

The chemical composition of the system does not change with time: there are no reactions in progress.

A glass of water and ice that is no longer melting is in phase equilibrium.

To say that a system is in equilibrium
all four must hold at the same time

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Quick check

Which of these systems is in equilibrium?

Freshly poured coffee cooling down

No. Thermal equilibrium is missing.

A pot of water boiling over high heat

No. The mass of vapor keeps changing.

A closed bottle left forgotten on the table

Yes. Nothing changes with time anymore.

It only takes one of the four to fail for there to be no equilibrium.

And without equilibrium I cannot speak of a state.

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The state postulate

A system has dozens of properties.

Do I have to measure them all to know what state it is in?

No. Just

2

well-chosen properties are enough

The rest are determined automatically.

That is what the state postulate says.

The state postulate

The state of a simple compressible system is completely specified by two independent intensive properties.

Two words in that statement must be understood well.

simple compressible

independent

Simple compressible system

What is special about that kind of system?

That the only thing that matters to it
is compressing or expanding

And that is the vast majority of the systems we are going to analyze: gases and liquids inside containers.

Simple compressible

A system that lacks the following effects:

electrical

magnetic

gravitational

motion

surface tension

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Independent properties

And what does it mean for two properties to be independent?

That I can change one
while keeping the other fixed

If when changing T the other changes on its own, then they are not independent and they are of no use to fix the state.

Independent

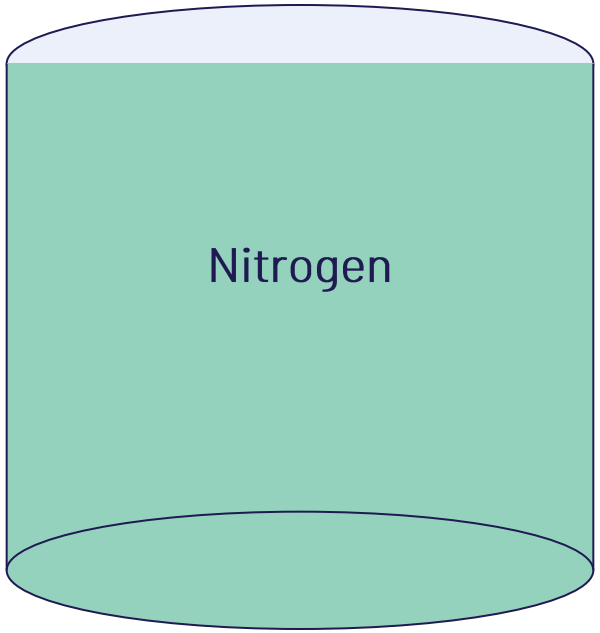
One of them can vary while the other is held constant.

And both must be intensive.

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Example

A tank with nitrogen



$$T = 25\ °C$$

$$v = 0.9\ m^3/kg$$

Two intensive and independent properties.

The state is completely fixed: all the other properties are already determined.

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Careful with this trap

Water boiling in an open pot. I give you the temperature and the pressure.
Is the state fixed?

$T = 100\ °C$

$P = 1\ atm$

No. While the water is boiling, T and P are not independent:
at 1 atm water boils at 100 °C and that is that

If I fix one, the other is tied to it. They are of no use as a pair.

There you would have to use another property, for example the specific volume.

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Before we continue...

A tightly closed thermos has been on the desk for three days. Which equilibria is it in?

All four. If nothing changes with time, the system is in equilibrium.

Why does classical thermodynamics insist on studying only equilibrium states?

Because out of equilibrium the properties do not have a single value throughout the system.

A gas is at a certain temperature and a certain density. Can I fix its state with that?

Yes. Both are intensive and independent, which is what the postulate requires.

Are temperature and mass enough to fix the state of a simple compressible system?

No. m is extensive and the postulate requires two intensive properties.

Now a case where equilibrium breaks all at once.

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Food for thought

A sealed soda has been on the table all afternoon. You come and open it: it starts to fizz, and after a while it settles down.

At which of these moments can I speak of a state?

Sealed on the table Yes, there is a state	Right when it is opened There stops being one
While it fizzes There is no state	Once settled New state

Which of the four equilibria broke first?

The key

On opening, the pressure drops suddenly: mechanical equilibrium breaks, and with it phase equilibrium, because the dissolved gas escapes.

During the fizzing the properties do not have a single value, so there is no state to describe.

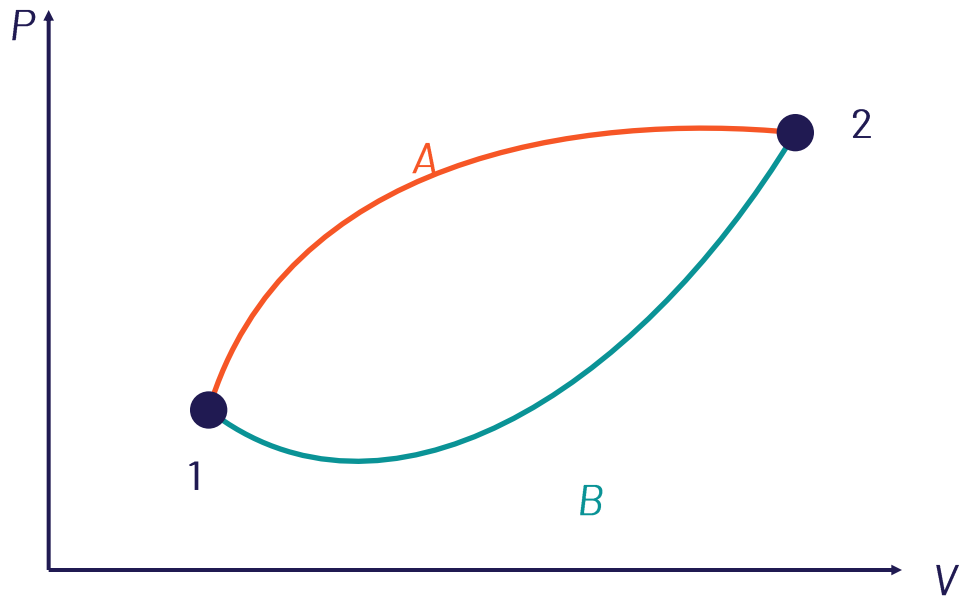
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Processes and cycles



Processes and cycles

I already know where the system started and where it ended.
Does that give me the whole story?



No. I still need to know
which way it went

Two different paths between the same two states give different results

That journey from one state to another is what we call a process.

Process and path

Two words that sound similar and are not the same

Process

the change itself, from one equilibrium state to another

Path

the series of intermediate states it goes through

To describe it

I need:

The initial state

The final state

The path followed

The interactions with the surroundings

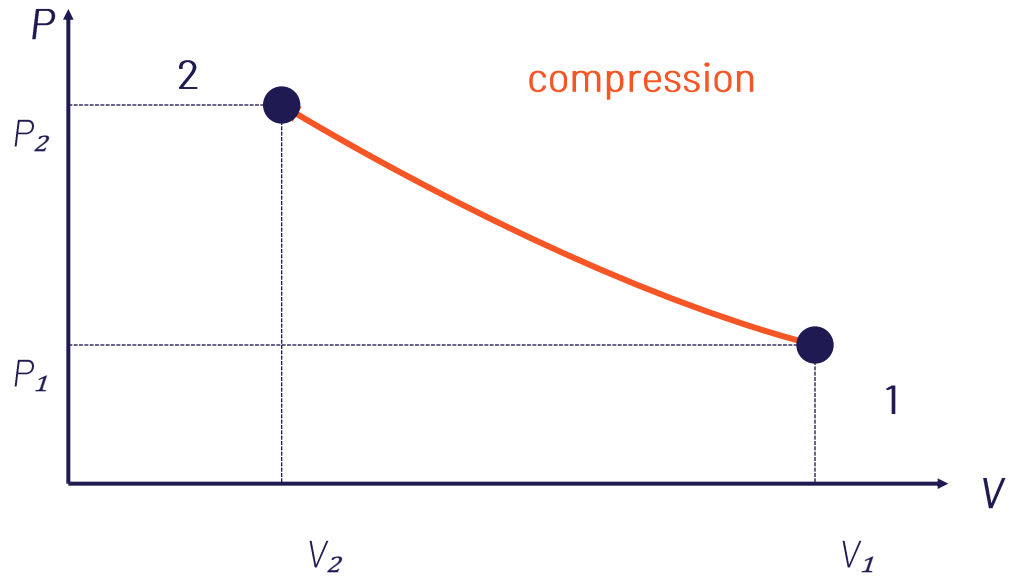
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Drawing the process

I compress a gas in a piston–cylinder device. How do I draw what happened?

On a pair of axes
P versus V

Each point on the curve
is an equilibrium state



I can only trace the curve if the process passes through equilibrium states one after another.

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The prefix iso

Isothermal, isobaric, isochoric, isentropic...

What do they all have in common?

In all of them there is

a property that does not change

The word after the prefix tells which property it is.

Iso comes from Greek and means equal.

Processes with their own name

The first two

Isothermal

The temperature remains constant throughout the process

$$T = constante$$

Isobaric

The pressure remains constant throughout the process

$$P = constante$$

Just reading the name is enough to know which property stays put.

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Processes with their own name

And the other two

Isochoric

The specific volume remains constant throughout the process

$$v = constante$$

Isentropic

The entropy remains constant throughout the process

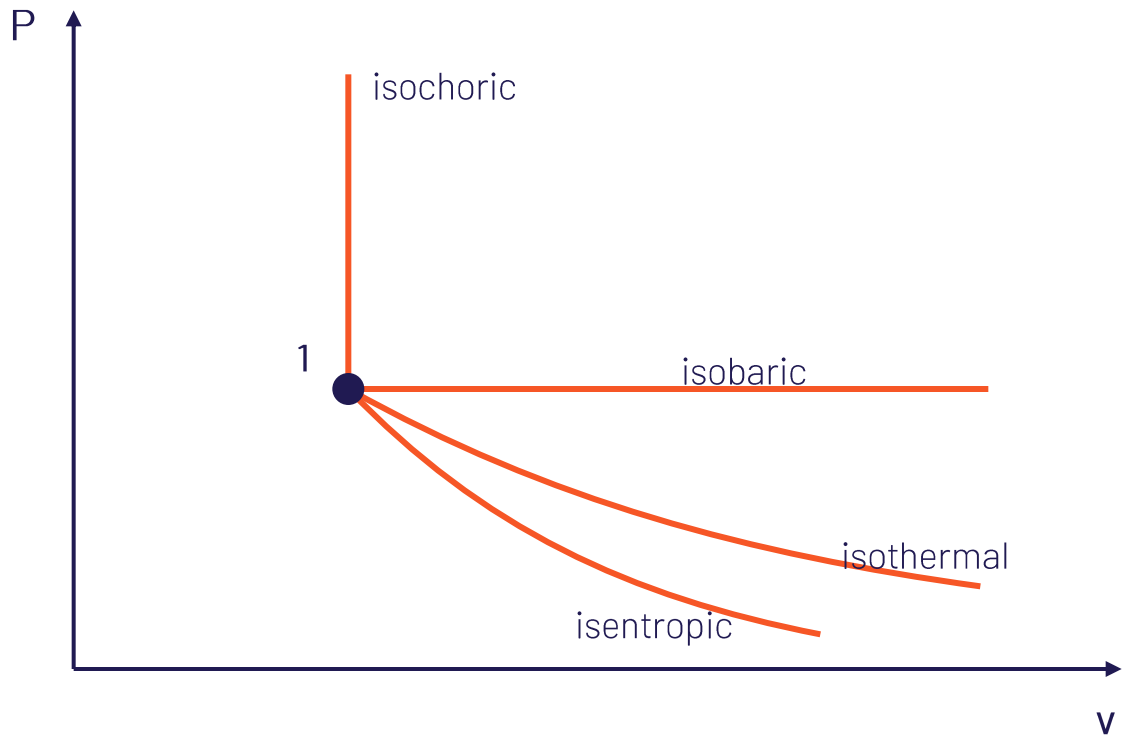
$$s = constante$$

We will see entropy later on; for now, keep the naming pattern in mind.

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The four in a single diagram

Each process has a characteristic shape in the P versus v plane



Isobaric Horizontal line

$P = cte$

Isochoric Vertical line

$v = cte$

Isothermal Hyperbola

$T = cte$

Isentropic Steeper curve

$s = cte$

Just by recognizing the shape of the curve you already know which process you are being shown.

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Quick check

What type of process is each one?

A sealed balloon that warms up in the sun and slowly inflates, always at street pressure

Isobaric

A rigid steel tank into which I add heat

Isochoric

A gas compressed very slowly inside a water bath at fixed temperature

Isothermal

The key is always to ask which property remains constant.

In the rigid tank the volume cannot change, and neither can the mass.

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Cycle

And what if the system, after going around several times, ends up exactly where it started?

Then it went through
a cycle

Your car's engine and your home refrigerator work by repeating a cycle over and over.

Cycle

A series of processes in which the final state is identical to the initial one: the system returns to where it started.

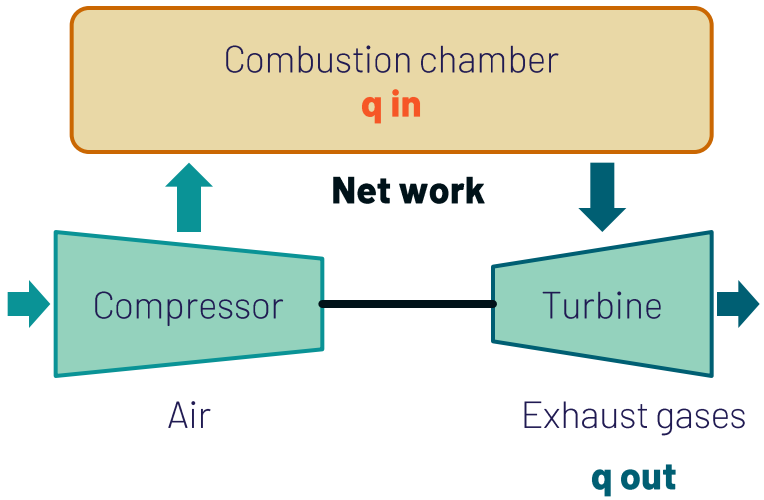
All its properties return to their starting value.

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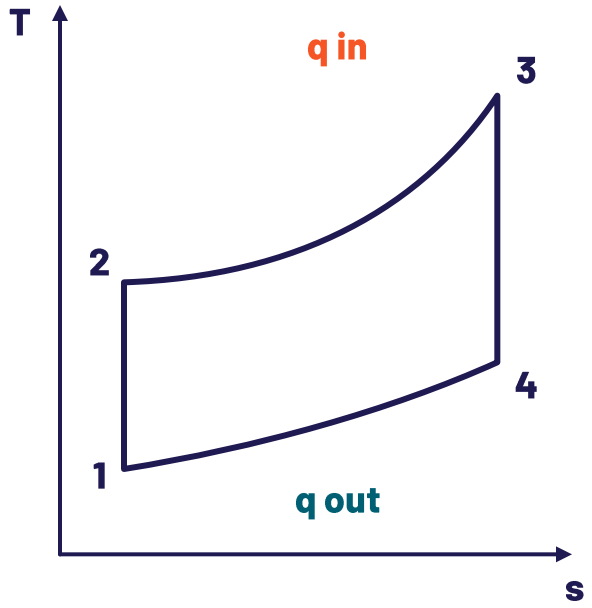
A real cycle

The gas turbine: air enters, is compressed, fuel is burned, the gas expands and leaves

Gas turbine · open cycle



T-s diagram



Four processes chained together
one after another

And when the fourth ends
it returns to state 1

That is why the diagram of a cycle always closes on itself.

Steady flow

A boiler has been running for eight hours. Is anything changing inside?

Fluid enters and leaves nonstop,
but nothing changes with time

Each point of the equipment has its own temperature value, and that value stays the same hour after hour.

Steady

Not changing with time. Properties may vary from point to point, but not from one instant to another.

The opposite:

transient

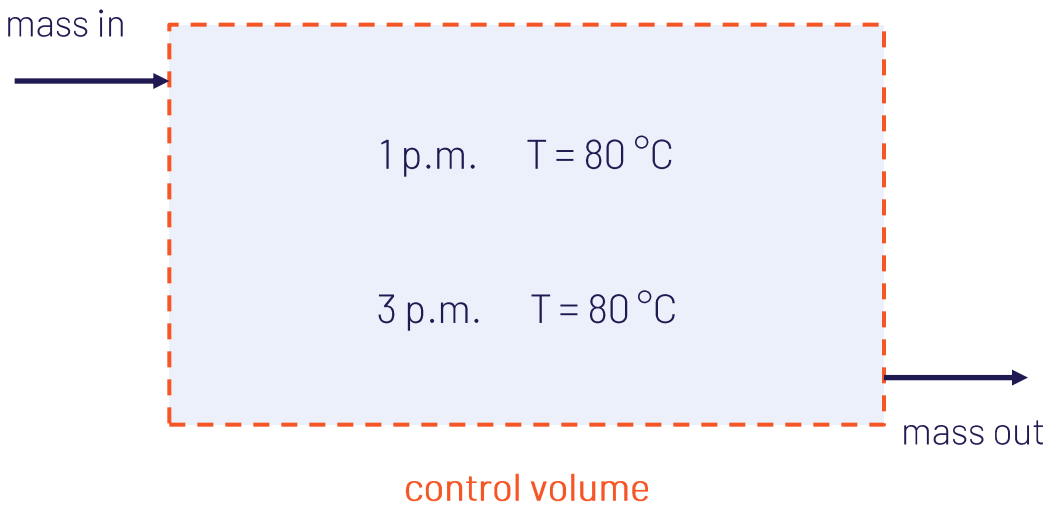
when it does change with time.

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Steady-flow equipment

A good part of equipment works this way

- Turbines
- Pumps
- Boilers
- Condensers
- Heat exchangers



Mass enters and leaves, but nothing changes with time

They are all designed to operate for long periods under the same conditions.

A power plant or a refrigeration system works the same way.

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From the diagram to reality

Some steady-flow equipment



Turbine



Centrifugal pump



Boiler



Heat exchanger

Quick check

Steady or transient?

A ceiling fan that has been on all night at the same speed

Steady

The car engine during the first minute after a cold start

Transient

A tire being inflated with the compressor

Transient

The deciding question is always the same:

if I come back in an hour, will I find the same thing?

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Before we continue...

Two processes take the gas from the same state 1 to the same state 2 by different paths. Are they the same process?

No. They share the endpoints, but the path is part of the description.

If a system completes a cycle, how much did its temperature change at the end?

None. It returns to the initial state, so every property returns to its starting value.

In a closed rigid tank that is heated, which process is it and why?

Isochoric. The volume and the mass are fixed, so v cannot change.

In a turbine in normal operation, is the temperature the same at all its points?

No. It varies from point to point; what does not change is with time.

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Food for thought

Your home refrigerator has been running all day. You open the door for a minute looking for something, and close it.

Answer for each case

The refrigerant goes through a cycle Yes, always	With the door closed Steady
With the door open Transient	Half an hour later Steady again

Why is the cycle not interrupted when the door is opened?

The key

The refrigerant keeps going around the same closed circuit: it leaves the compressor and returns to it. That is a cycle, whether you open the door or not.

What changes is that, while warm air is entering, conditions no longer repeat from instant to instant.

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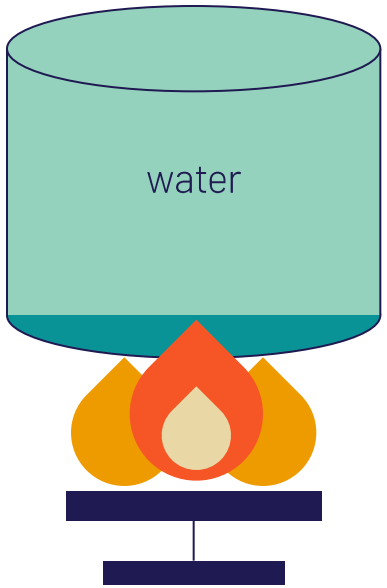
Laws of thermodynamics

Temperature and pressure

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Temperature and pressure

I put a pot on the stove and the water heats up.
What is happening in there?



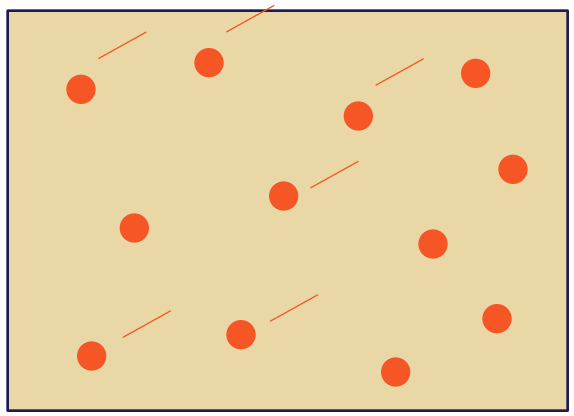
The molecules start to
move faster

And that is exactly what
temperature measures

Adding heat or work to a substance generally raises its temperature.

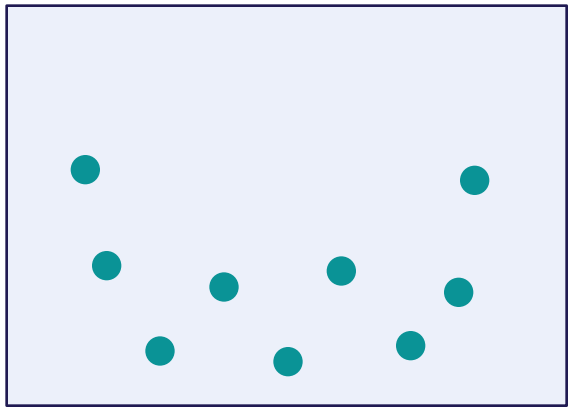
Temperature

And what exactly is temperature?



high temperature

they move fast



low temperature

they move slowly

The faster they move, the higher the temperature.

Temperature

A measure of the average kinetic energy of the atoms or molecules that make up the substance.

It does not measure how much energy there is, but how agitated the matter is.

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Zeroth law

I dip the thermometer in the coffee and its reading stabilizes at 70 °C.
Why is the thermometer's temperature also the coffee's?

If two systems are in thermal equilibrium with a third, then they are in thermal equilibrium with each other.

The thermometer is that third system.

When it stops rising, it is already at the same temperature as the coffee.

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The four laws

To place it: where the one we have just seen fits

Zeroth law
Defines temperature and makes it possible to measure it

First law
Energy is transformed; it is neither created nor destroyed

Second law
The entropy of an isolated system never decreases

Third law
The entropy of a pure crystalline substance tends to zero as absolute zero is approached

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Temperature scales

Someone had to decide that water freezes at zero.

What is a scale built on?

On states that are easy to reproduce in any laboratory in the world

Ice point

Ice and water in equilibrium with vapor-saturated air, at 1 atm

$0\ °C = 32\ °F$

Steam point

Liquid water and vapor in equilibrium, without air, at 1 atm

$100\ °C = 212\ °F$

With two fixed points I can already graduate everything in between.

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Relative scales

The two you use every day, each from a different system of units

Celsius
International system
measured in degrees Celsius

Fahrenheit
English system
measured in degrees Fahrenheit

Both are relative: their zero was set by a person, not by nature.

That is why negative temperatures exist in both, and that is why something better had to be invented.

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Absolute scales

What if I want a scale that does not depend on any substance?

Kelvin
the absolute one of the international system

Rankine
the absolute one of the English system

Neither of the two has negative values.

Absolute scale

Temperature scale independent of the properties of any substance.

Its zero is absolute zero, not a point chosen for convenience.

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Conversion between scales

You only have to shift the zero

$$T\ (K) = T\ (°C) + 273.15$$

$$T\ (R) = T\ (°F) + 459.67$$

And something used constantly in energy balances:

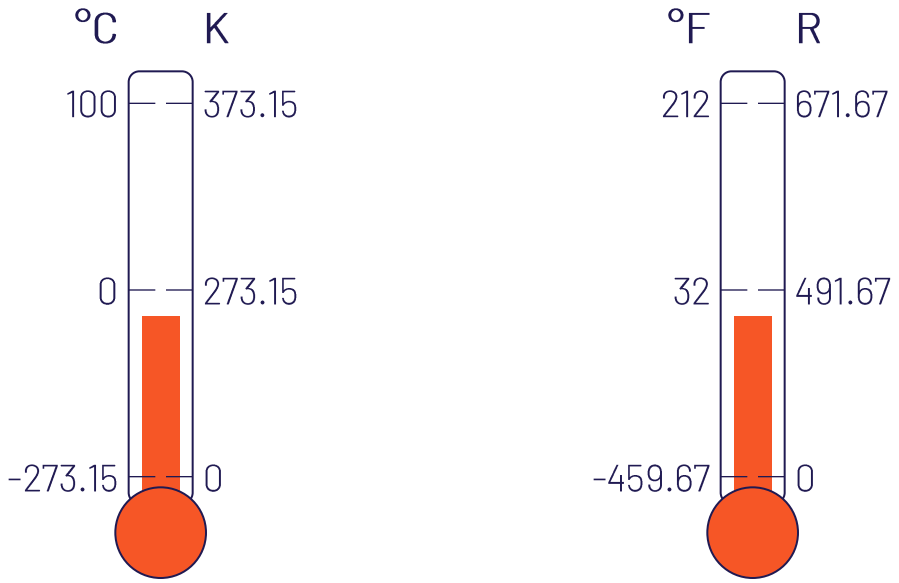
$$\Delta T\ (K) = \Delta T\ (°C)$$

A temperature difference has the same value in kelvins as in degrees Celsius.

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The four scales side by side

The same three reference points, read on each scale



The same three states, read on four scales

Steam point

$100\ °C \quad 373.15\ K \quad 212\ °F \quad 671.67\ R$

Ice point

$0\ °C \quad 273.15\ K \quad 32\ °F \quad 491.67\ R$

Absolute zero

$-273.15\ °C \quad 0\ K \quad -459.67\ °F \quad 0\ R$

Notice that the size of the degree is the same in Celsius and Kelvin, and in Fahrenheit and Rankine.

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Exercise

In a heat exchanger, air enters at 27 °C and leaves at 227 °C.

Data: $T_1 = 27\ °C$ $T_2 = 227\ °C$

Calculate:

a) the two temperatures in kelvin

b) the temperature change, in °C and in K

c) the inlet temperature in degrees Fahrenheit

Part b) is where most people go wrong.

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Solution

a) I add 273.15 to each one

$$T_1 = 27 + 273.15 = 300.15\ K \qquad T_2 = 227 + 273.15 = 500.15\ K$$

b) The difference, in each scale

$$\Delta T = 227 - 27 = 200\ °C$$

$$\Delta T = 500.15 - 300.15 = 200\ K$$

c) I convert to Fahrenheit

$$T_1 = 1.8 \cdot 27 + 32 = 80.6\ °F$$

The change gives 200 on both scales: you do not add 273.15 to a difference.

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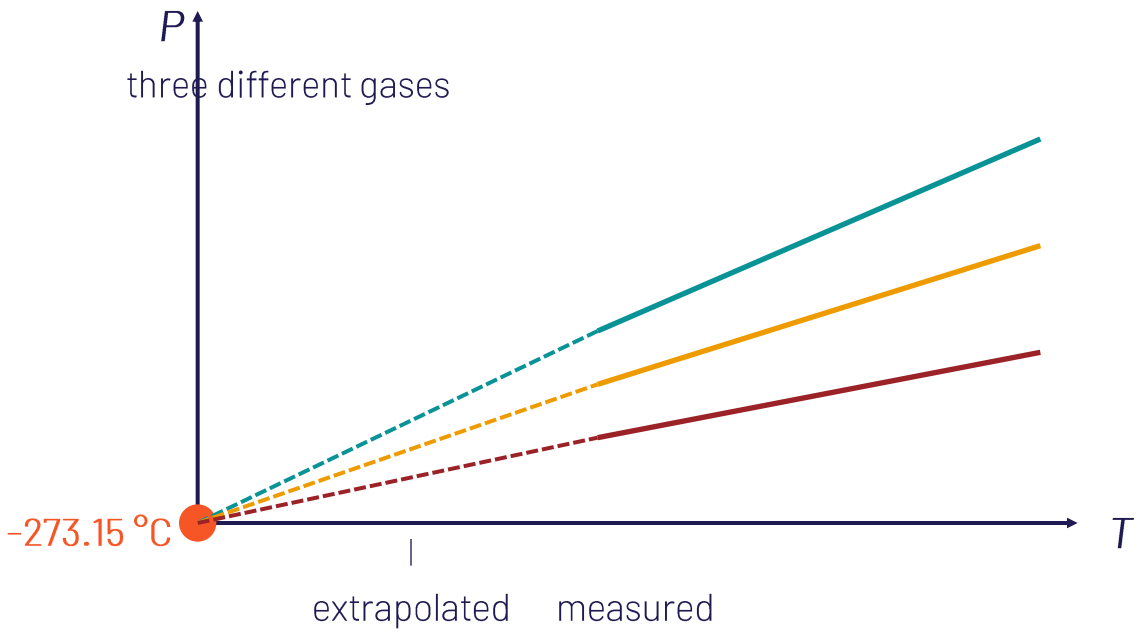
Absolute zero

And where did that odd number of 273.15 come from?

From measuring the pressure of several gases at constant volume

All the lines intersect at

$-273.15\ °C$



No matter which gas is used, the extrapolation always reaches the same point.

There the pressure would be zero: it cannot go any lower.

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Quick check

Three heating conversions

Water boils at 100 °C. How much is that in kelvin?

$373.15\ K$

A process rises from 20 °C to 80 °C. How much did it rise in kelvin?

$60\ K$

Can a body be at -5 K?

$No\ existe$

The second one is where people go wrong most: you do not add 273 to a difference.

And below absolute zero there is nothing to measure.

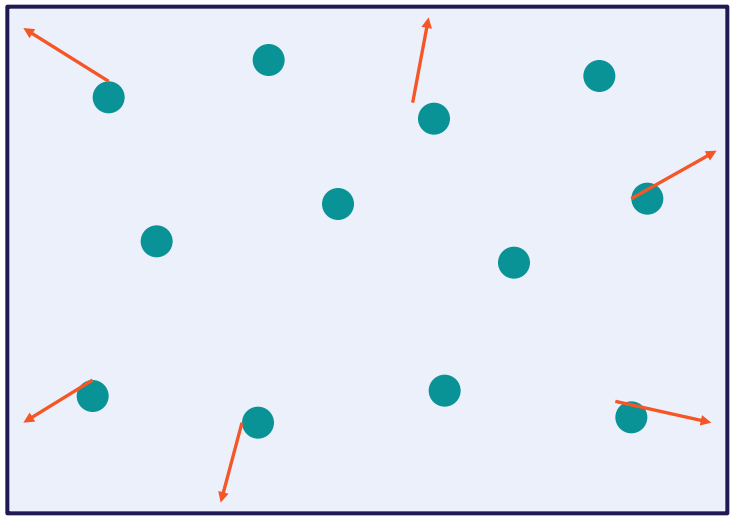
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Pressure

I inflate a balloon and it becomes taut, about to burst.
Who is pushing the walls from inside?

The molecules collide against
the walls nonstop

Each collision changes their momentum and that produces a force



each collision pushes the wall

If I raise the temperature, they collide harder and the pressure rises.

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Pressure

All those collisions, added up, feel like a single thing

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

$$\frac{N}{m^2} = Pa$$

Notice that pressure depends on area: the same force over less area gives more pressure.

Pressure

Normal force exerted by a fluid per unit area.

In solids the equivalent quantity is normal stress.

Pressure units

The pascal is tiny, so in practice these are used

$$1\ bar\ = 100\ 000\ Pa = 100\ kPa = 0.1\ MPa$$

$$1\ atm\ = 101\ 325\ Pa = 101.325\ kPa = 1.01325\ bar$$

$$1\ kgf/cm^2\ = 98\ 070\ Pa = 0.9807\ bar = 0.9679\ atm$$

The atmosphere is the pressure of air at sea level.

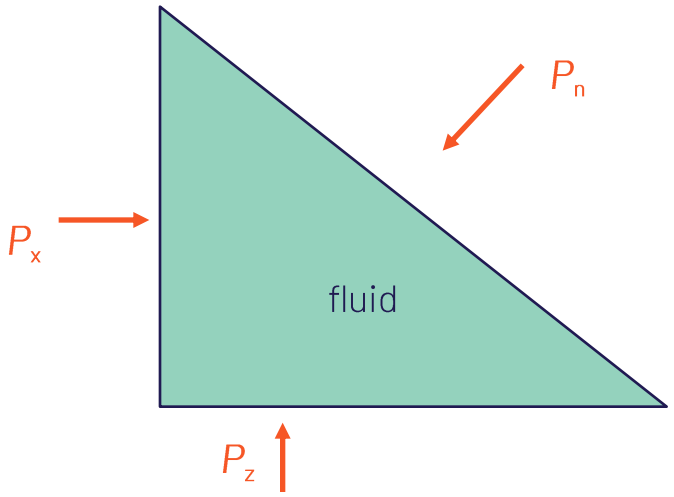
A bar was invented precisely to have a round number close to it.

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Pascal's law

I stand at a point inside the water and measure the pressure in several directions.

Does the value change depending on which way I measure?



No. It is the same in all of them

$$P_x = P_z = P_n = P$$

It comes from setting up the force balance on a fluid wedge and making it infinitely small

The pressure at a point in a fluid has the same magnitude in all directions.

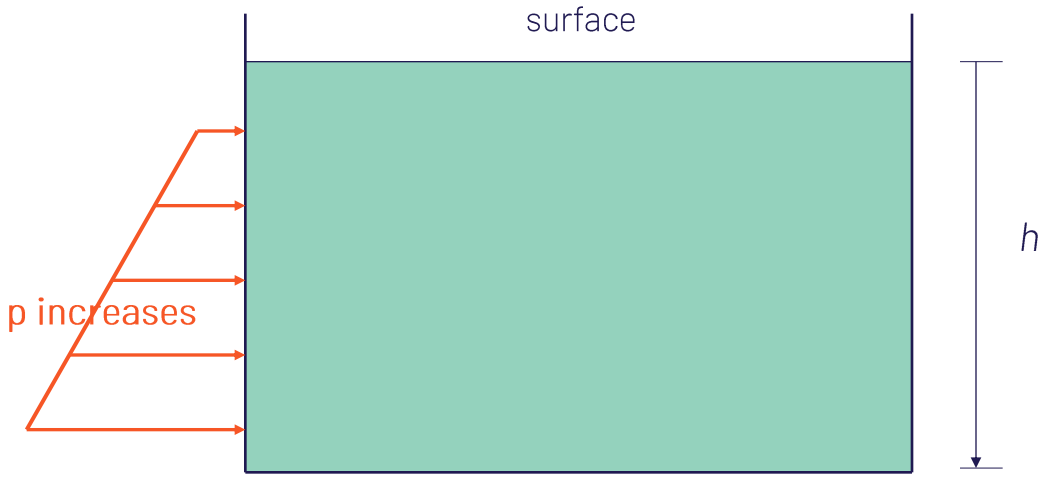
And it always acts perpendicular to the surface it pushes on.

Pressure with depth

You dive into a pool and your ears hurt. Why?

Because above you there is more and more weight of water

$$p = p_{atm} + \rho g h$$



Two points at the same depth in the same fluid have the same pressure, even if the container has odd shapes.

What matters is the height of the column, not the shape of the container.

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Quick check

A water tank with several points marked at different heights.

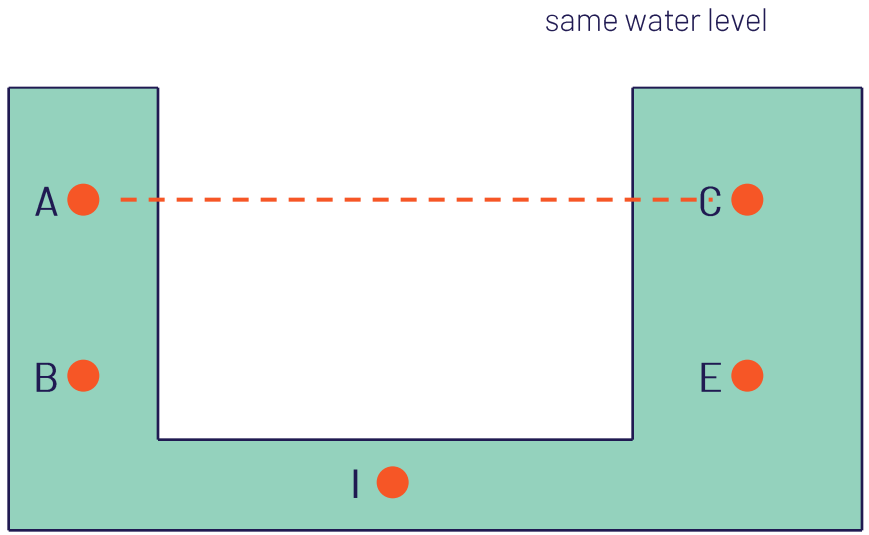
Compare the pressures

A and C: same pressure (same depth)

$$p_A = p_C$$

I is deeper than E, so its pressure is higher

$$p_I > p_E$$



To compare two pressures just look at the depth, not the width of the container.

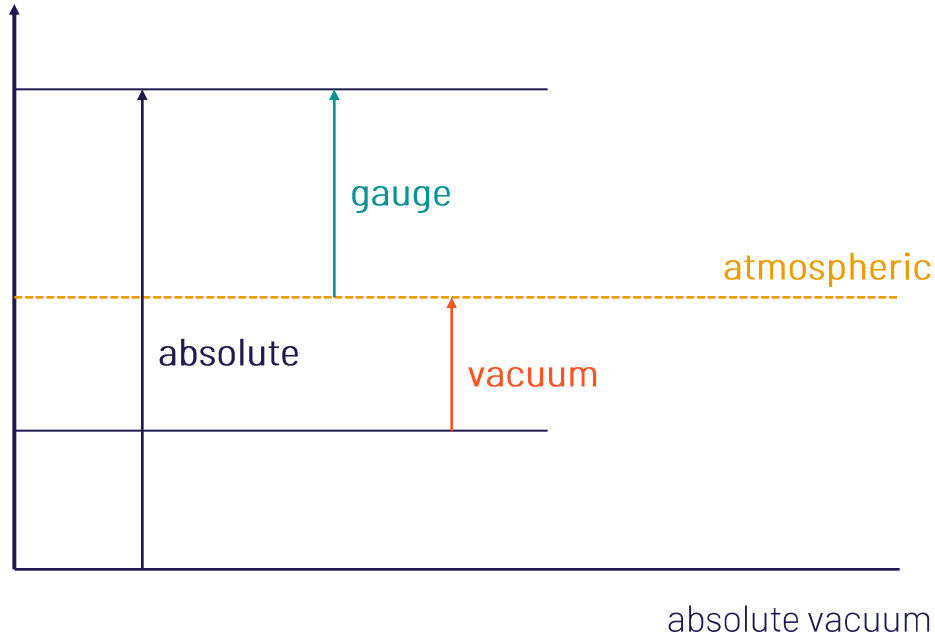
And if along the way there is another fluid, such as mercury, the density must be changed.

Absolute and gauge pressure

A flat tire reads zero on the gauge.
Is there really no pressure inside?

Yes there is: one atmosphere
the gauge does not measure from zero, it measures from the surroundings

The true zero is absolute vacuum
and there really is nothing there



That is why there are two ways to report a pressure, and you have to say which one is being used.

Confusing them is one of the most expensive mistakes in engineering.

How they are related

The rule is a single one, and it works in both directions

$$P_{abs} = P_{atm} + P_{man}$$

Positive gauge
the system is above atmospheric

Negative gauge
it is vacuum: the system is below

In property tables absolute pressure is always used.

Instruments, on the other hand, almost always give you the gauge value.

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Exercise

The pump gauge reads 70 kPa while inflating a bicycle tire.

If the local atmospheric pressure is 104 kPa, what is the absolute pressure in the tire?

Data: $P_{man} = 70\ kPa$ $P_{atm} = 104\ kPa$

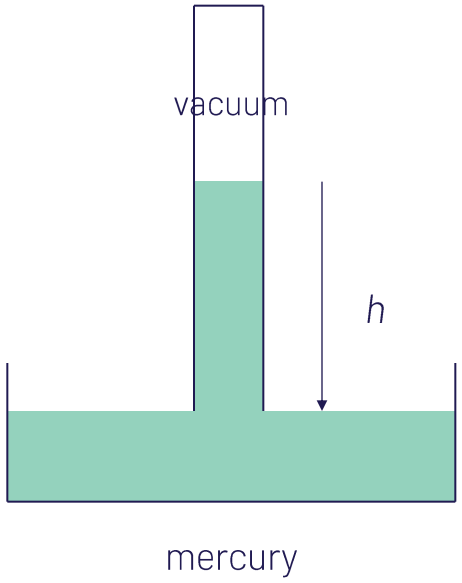
$$P_{abs} = P_{atm} + P_{man}$$
$$P_{abs} = 104\ kPa + 70\ kPa$$

$$P_{abs} = 174\ kPa$$

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Barometer

And how do I measure the pressure of the air around me?



Above the tube there is vacuum

$$P_{atm} = \gamma_{Hg} h$$

The mercury column is held up by the weight of the air.

Barometer

Instrument for measuring atmospheric pressure. It has been in use since the mid-seventeenth century.

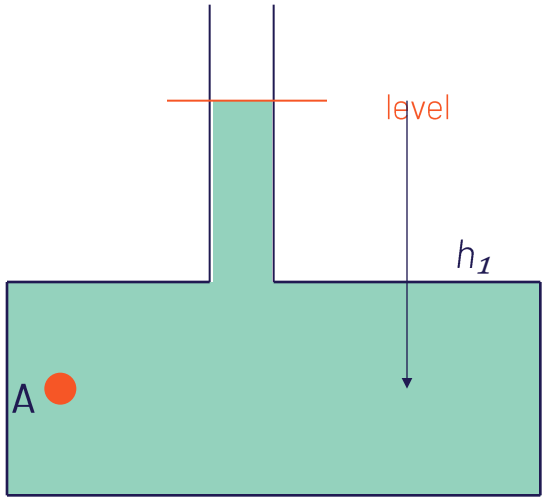
That is why atmospheric pressure is also called barometric pressure.

Liquid-column manometer

If the height of a liquid column depends on pressure,
can I use it in reverse to measure it?

Yes. The simplest one is a vertical tube open at the top, called a piezometer

$$P_A = P_0 + \gamma_1 h_1$$



open to the atmosphere at the top

You only need to read the height the liquid reaches to know the pressure.

But it only works with liquids and with positive gauge pressures.

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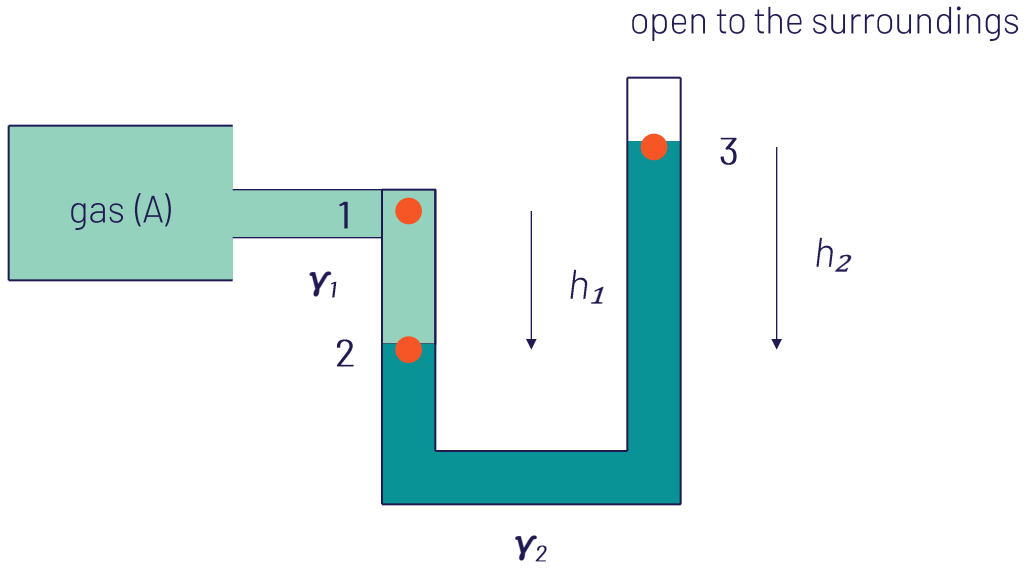
U-tube manometer

The piezometer falls short with gases and with vacuum.

The solution is to bend the tube

Now it works for gases and for negative gauge pressures

$$P_A + \gamma_1 h_1 - \gamma_2 h_2 = P_{atm}$$



The recipe: I start at one end, go down adding and go up subtracting.

When crossing from one fluid to another, I change the specific weight.

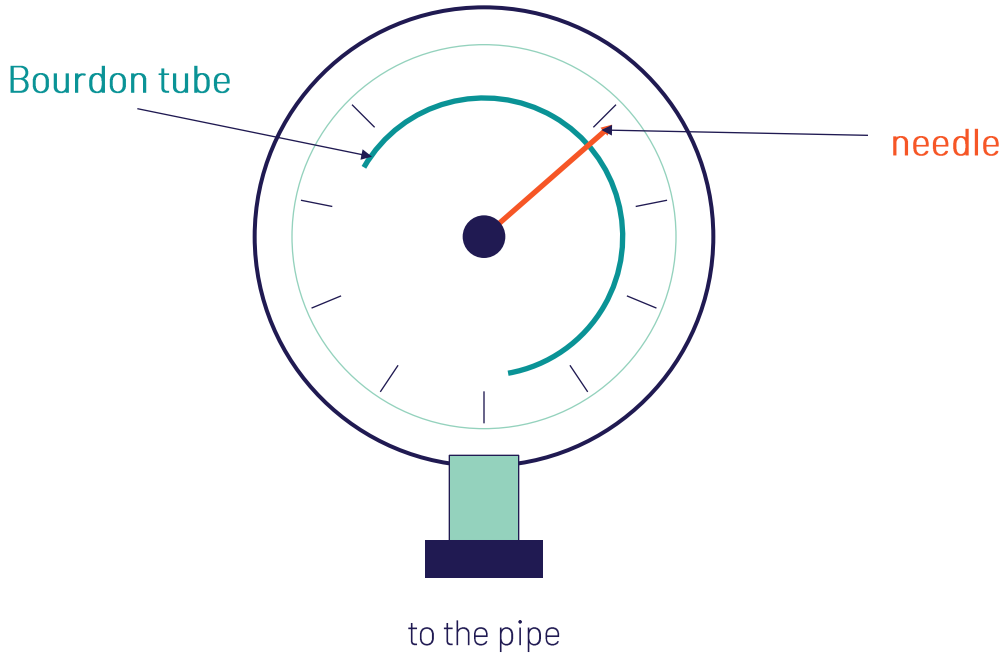
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Bourdon gauge

A liquid column is no good for 200 bar.
What does industry use then?

A curved metal tube that straightens when the pressurized fluid enters

That movement moves the needle
It is the most common one in industry



It covers very wide ranges and needs no reference liquid.

It reads zero when open to the surroundings: it measures gauge pressure.

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From the diagram to reality

The pressure instruments you will find in the laboratory



Bourdon gauge



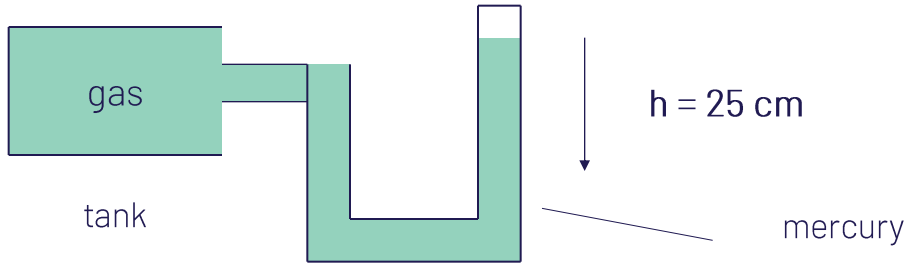
U-tube manometer



Aneroid barometer

Exercise

A U-tube manometer with mercury measures the pressure of a gas in a tank. The mercury column is displaced by 25 cm.



Data: $SG = 13.6 \quad h = 0.25\ m \quad \mathrm{P}_{atm} = 101.3\ kPa \quad g = 9.81\ m/s^2$

a) the gauge pressure of the gas

b) the absolute pressure of the gas

Start by finding the density of mercury.

Solution

First, the density of mercury from its specific gravity

$$\rho_{Hg} = SG \cdot \rho_{H_2O} = 13.6 \cdot 1000 = 13600\ kg/m^3$$

a) The mercury column gives the gauge pressure

$$\mathrm{P}_{man} = \rho g h = 13600 \cdot 9.81 \cdot 0.25 = 33354\ Pa = 33.4\ kPa$$

b) I add the atmospheric pressure

$$\mathrm{P}_{abs} = 101.3 + 33.4$$

$$\mathrm{P}_{abs} = 134.7\ kPa$$

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Before we continue...

Two bodies at different temperatures are put in contact. What guarantees that in the end they will read the same?

The zeroth law. It is what makes a thermometer meaningful.

A process goes from 300 K to 350 K. How much did it rise in degrees Celsius?

50 °C. A difference has the same value on both scales.

Do two points at the same depth in an oddly shaped container have the same pressure?

Yes. Only the column height matters, not the shape.

A gauge reads zero. What is the absolute pressure of the system?

The local atmospheric pressure. A reading of zero means it is equal to the surroundings.

Food for thought

You inflate your car tire in Barranquilla to 32 psi and drive up to Bogotá. On arrival you measure again with the same gauge.

What happens to each one?

The air inside Nothing escaped	Atmospheric pressure Dropped considerably
Absolute pressure Almost the same	Gauge reading Goes up

Why does it read more if nobody inflated the tire?

The key

The gauge does not measure the tire's pressure: it measures the difference against the outside air.

In Bogotá the outside air pushes less, so the difference grows.

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THANK YOU

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Thank you for your attention

If you have any questions, do not hesitate to get in touch



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