Essential Physics II

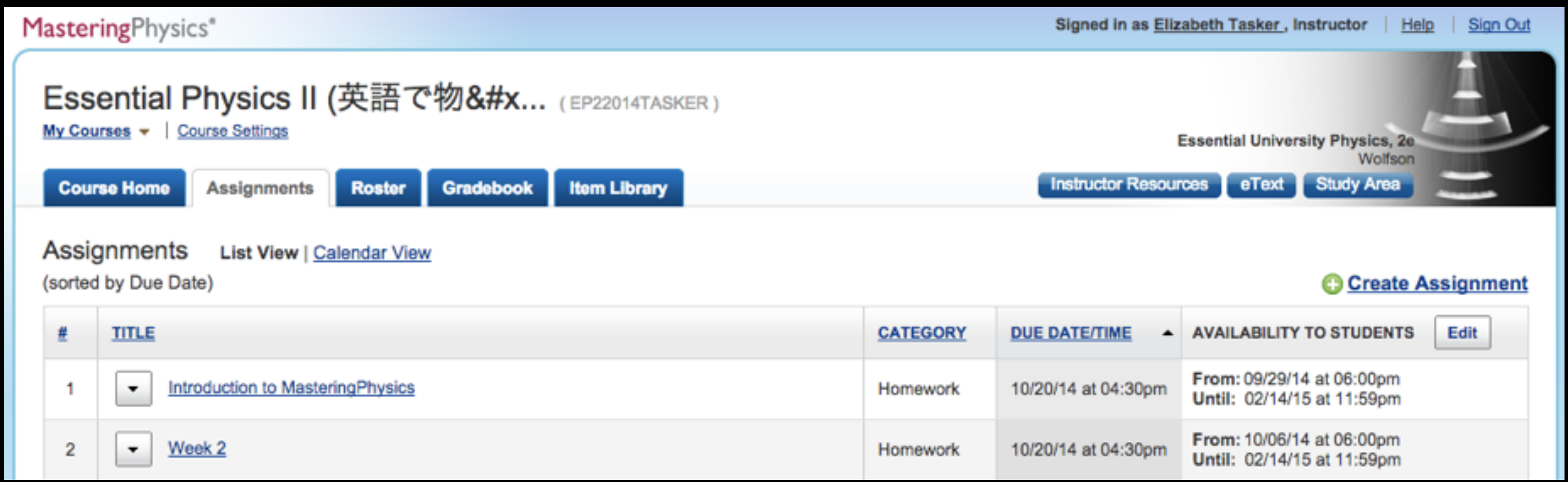
英語で物理学の

エッセンス II

Lecture 3:   15-10-15

Homework

If you did not do the homework... WHY?



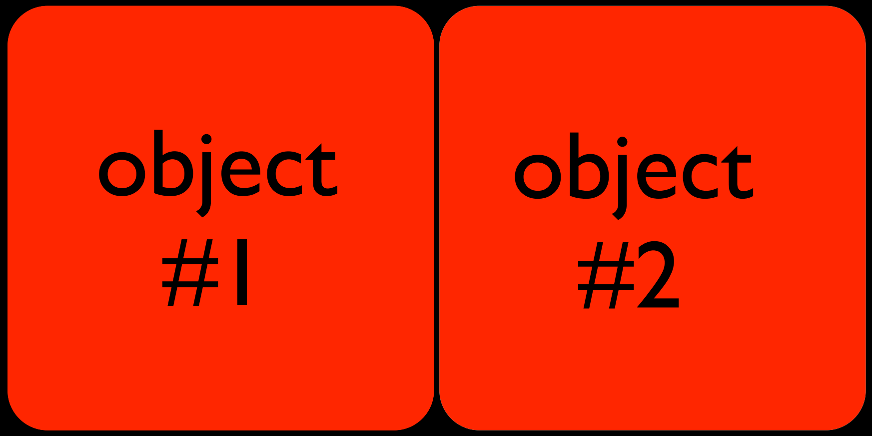
http://masteringphysics.com

http://astro3.sci.hokudai.ac.jp/~tasker/teaching/ep2

Last Lecture

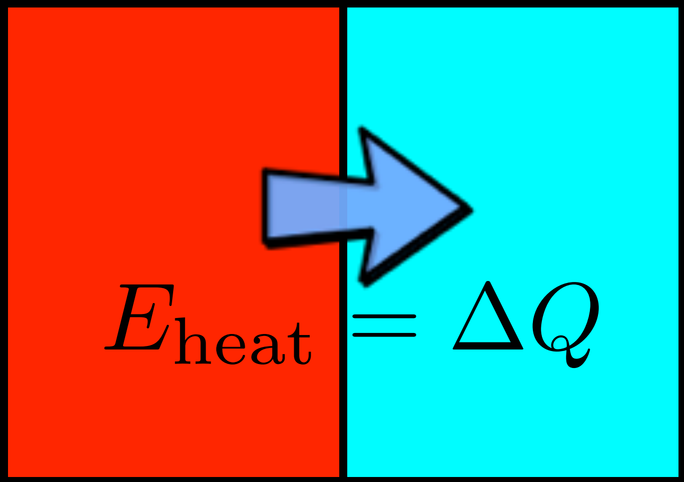
Temperature:

2 objects have the same T when in thermodynamic equilibrium



SI unit: kelvin [K]

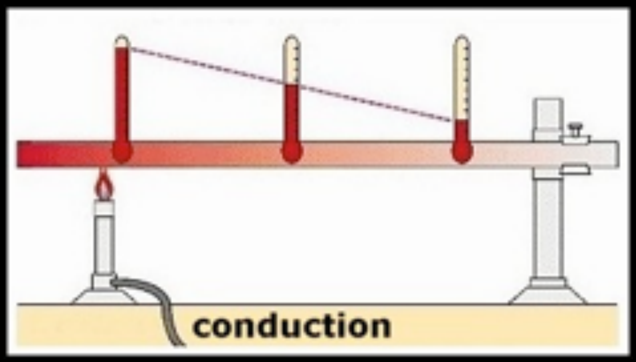
Heat is energy moving because of a difference in temperature (ΔT)

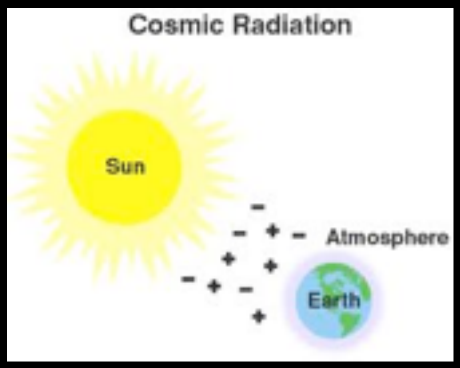


$$Q = mc\Delta T$$

specific heat

Heat can be transferred via conduction, convection and radiation





Last Lecture

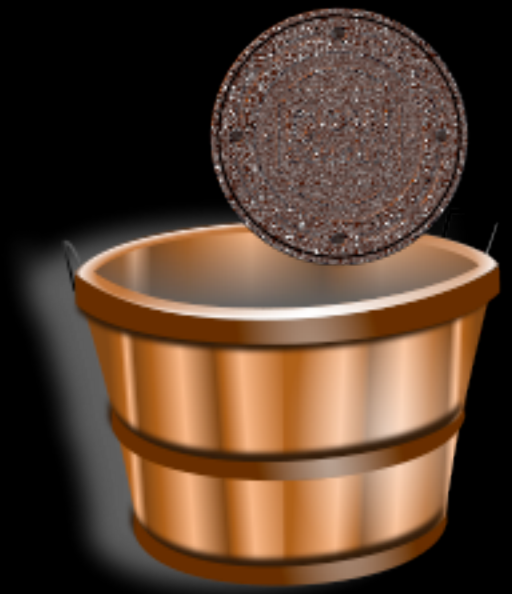
The specific heat (c) of water is greater than iron.

If you drop hot iron into a water bucket, the heat gained by the water is...

(a) larger than the heat lost by iron

(b) smaller than the heat lost by iron

(c) the same as the heat lost by iron

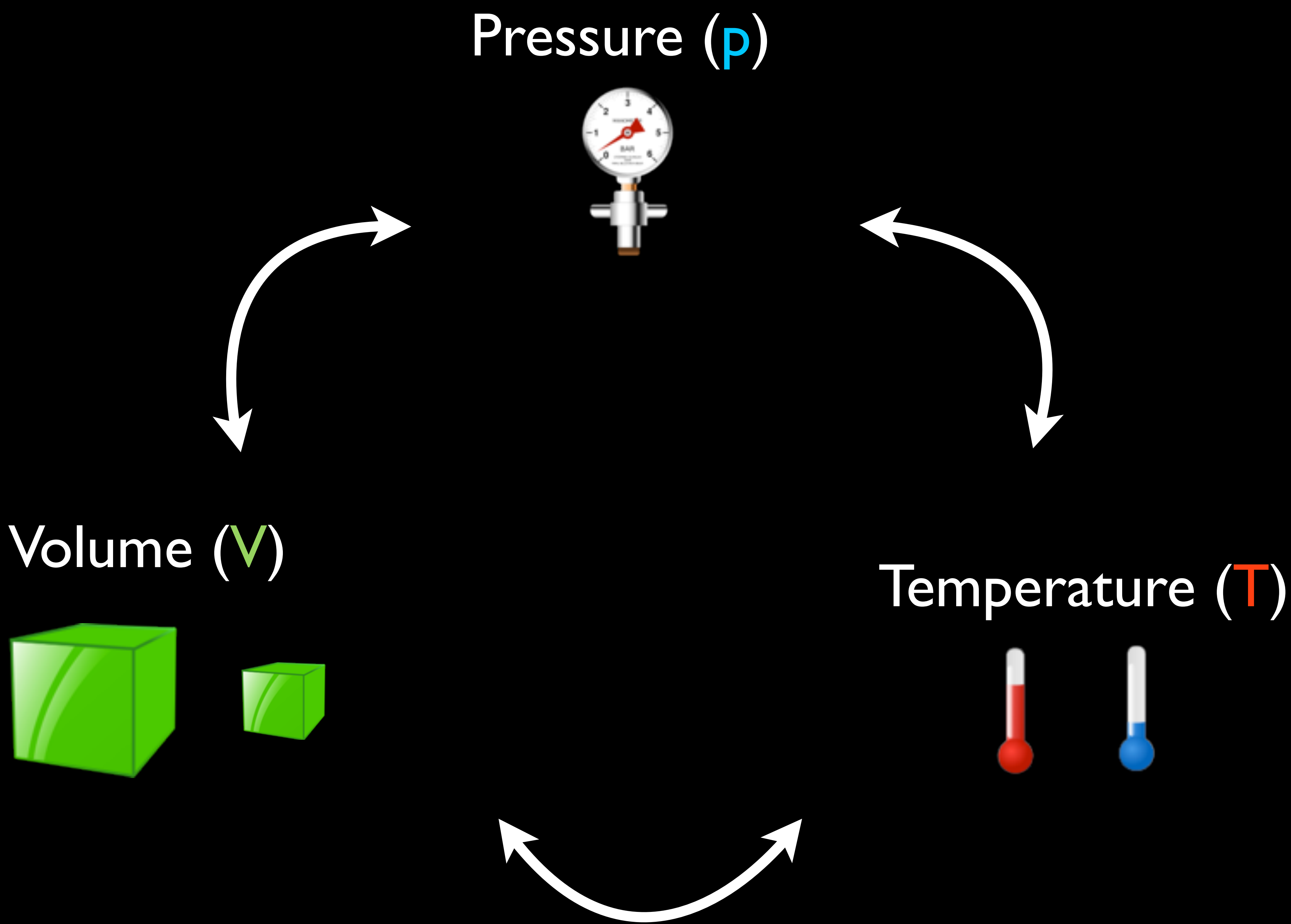


T is different, but energy is conserved

Heat and Matter

Ideal Gas Law

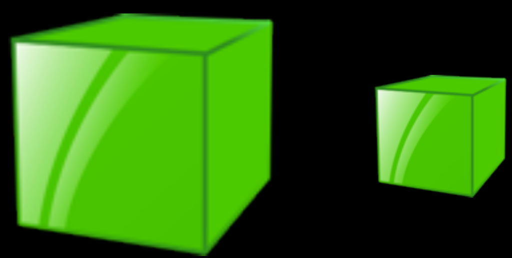
How are...

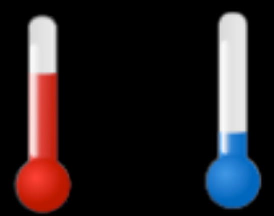


... related?

Ideal Gas Law

Volume (V) ⟷ Pressure (p) ⟷ Temperature (T)



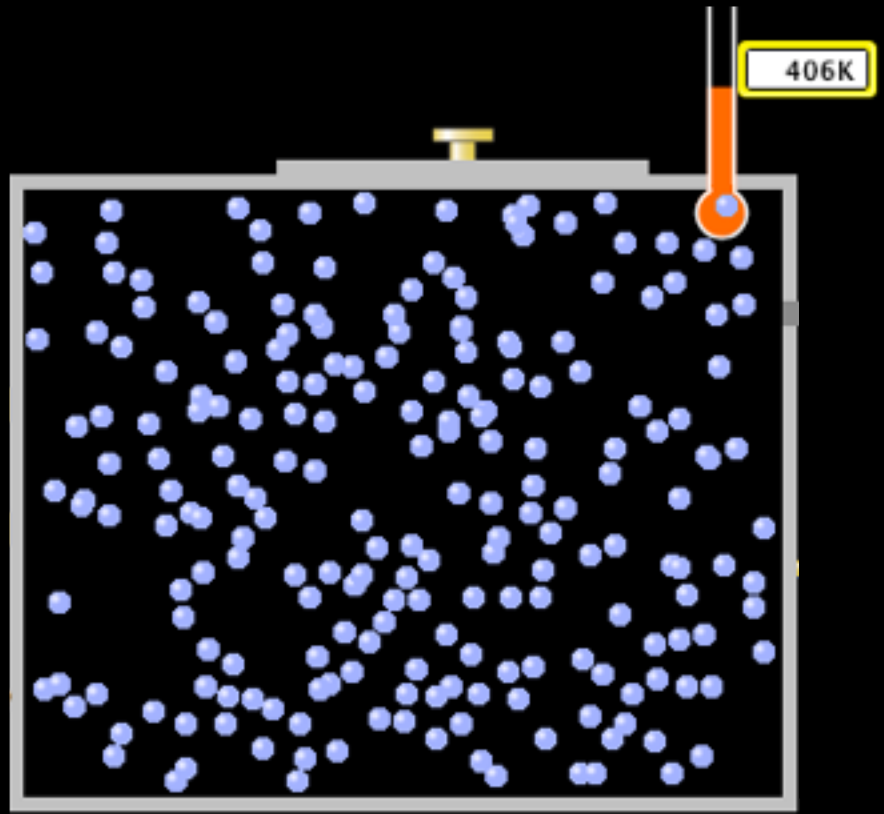


If V is constant, what happen to p if we lower T?

(a) Pressure goes down ↓

(b) Pressure goes up ↑

(c) Pressure stays the same



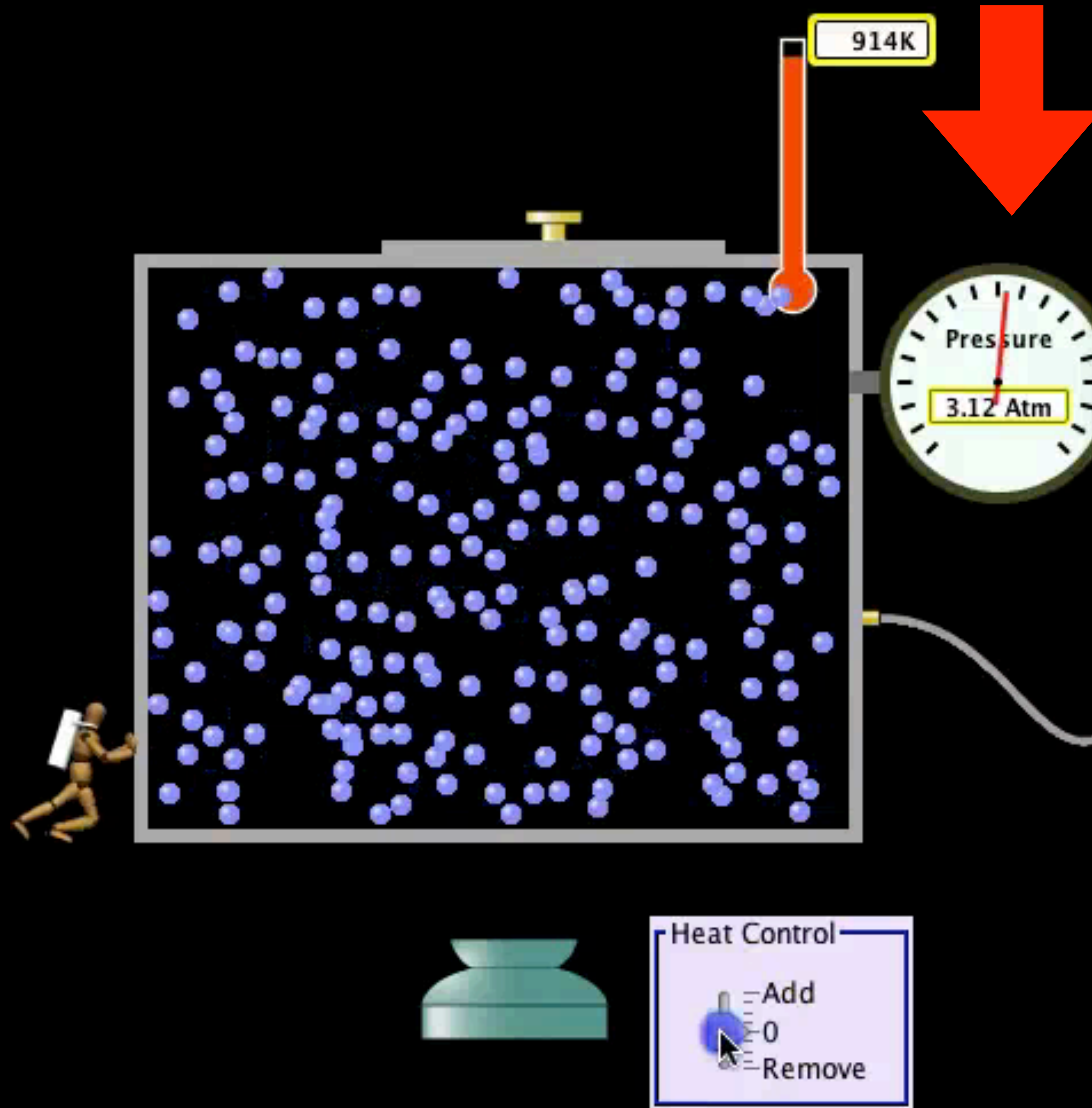
Ideal Gas Law

V is constant, 

T goes down ↓ 

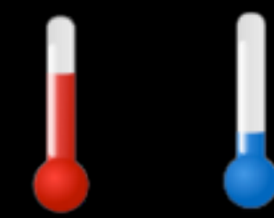
p … … goes down ↓

$$p \propto T$$



Ideal Gas Law

Volume (V) ↔ Pressure (p) ↔ Temperature (T)



If V is constant, what happen to p if we lower T?

(a) Pressure goes down ↓

$p \propto T$

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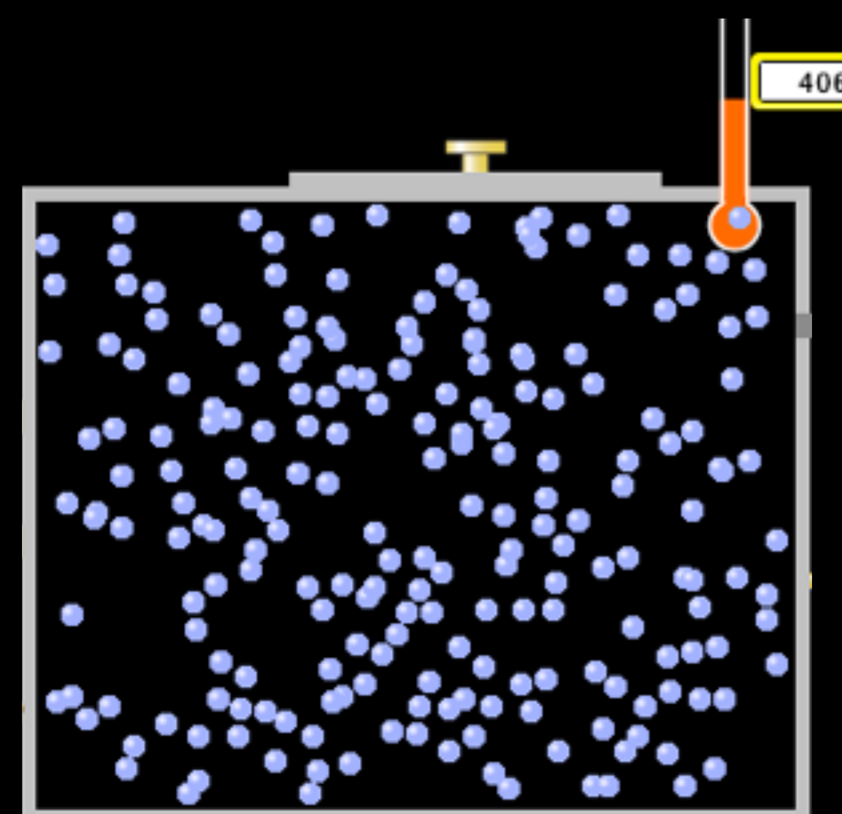
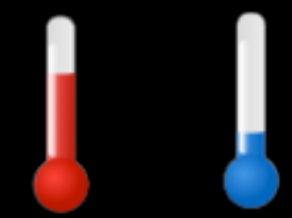


Ideal Gas Law

Volume (V) Pressure (p) Temperature (T)



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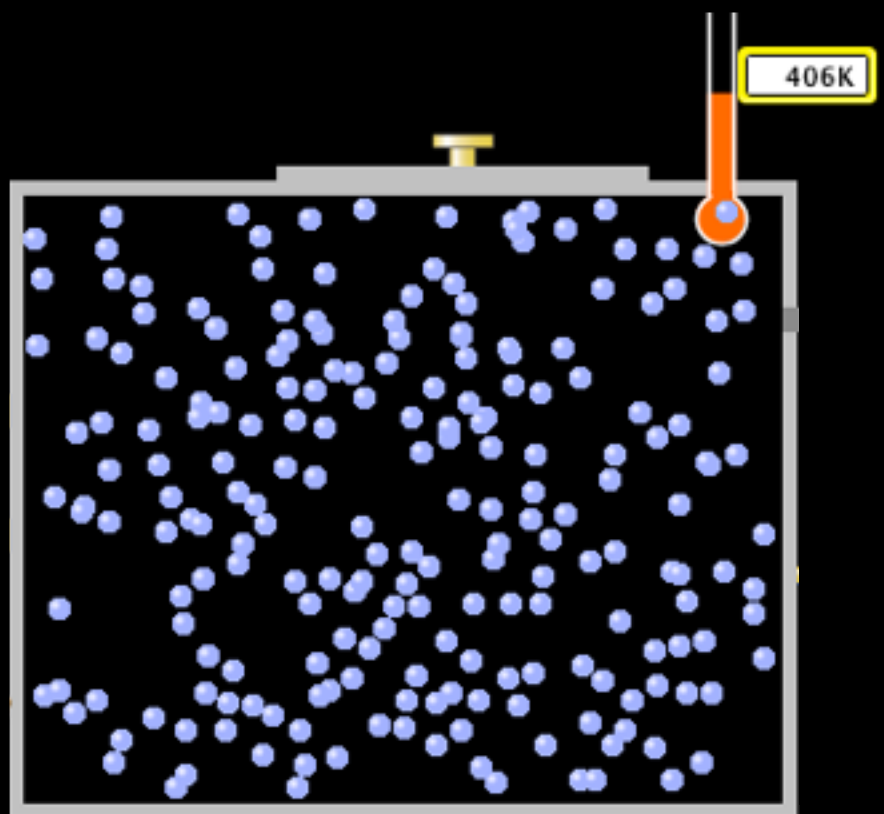
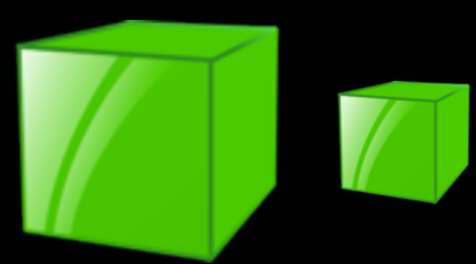


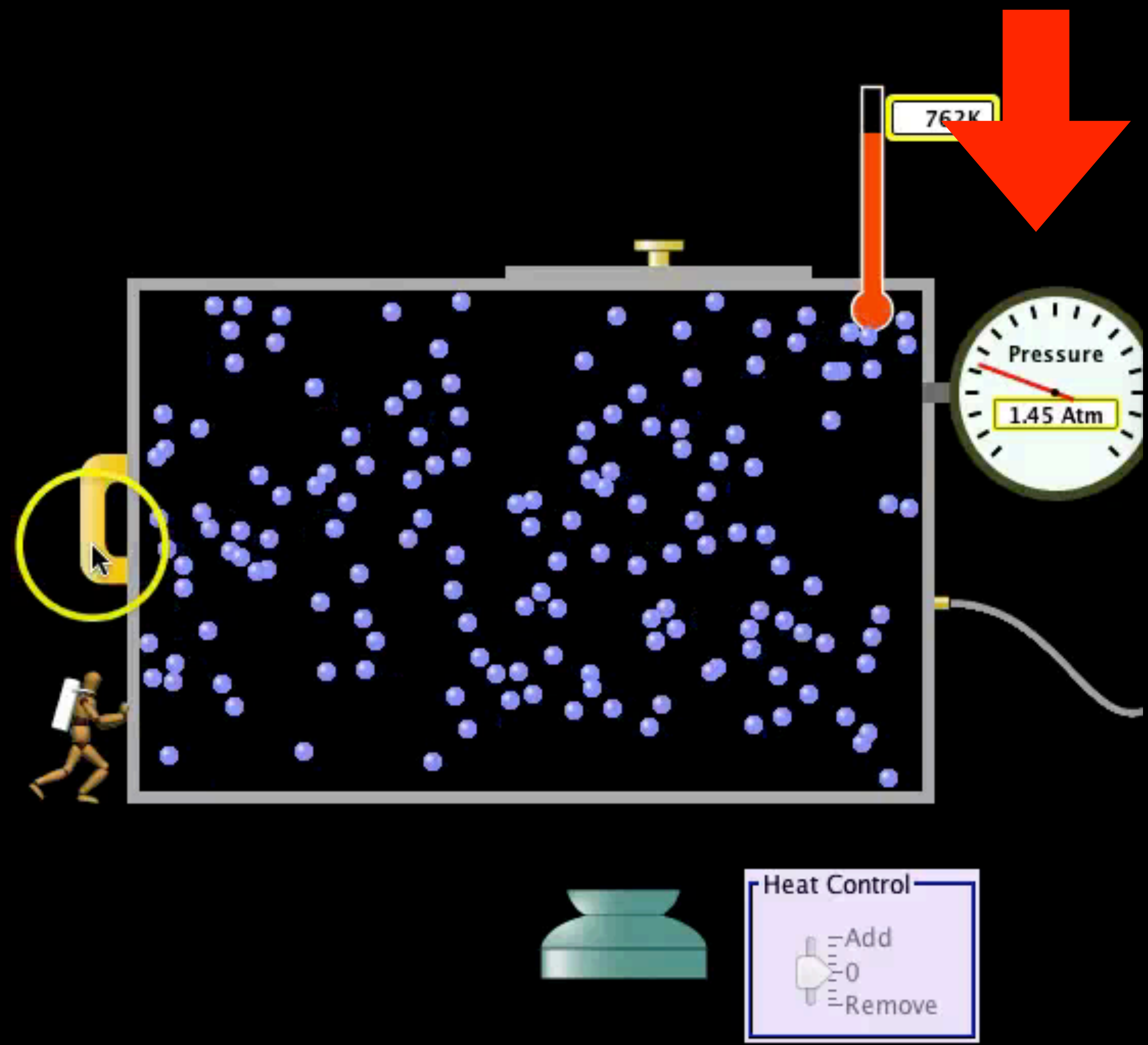
Ideal Gas Law

T is constant,

Lower V ↓



p ... ... goes up ↑



$$p \propto \frac{1}{V}$$

Ideal Gas Law

Volume (V) Pressure (p) Temperature (T)

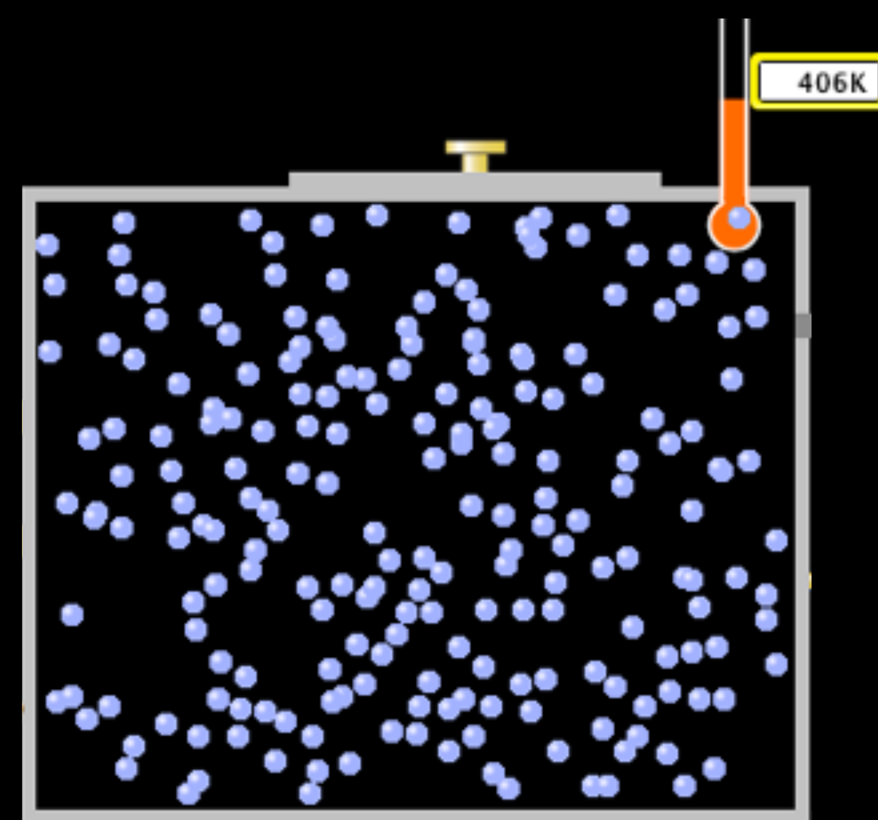
If T is constant, what happen to p if we lower V?

(a) Pressure goes down ↓

(b) Pressure goes up ↑

(c) Pressure stays the same

$$p \propto \frac{1}{V}$$



Ideal Gas Law

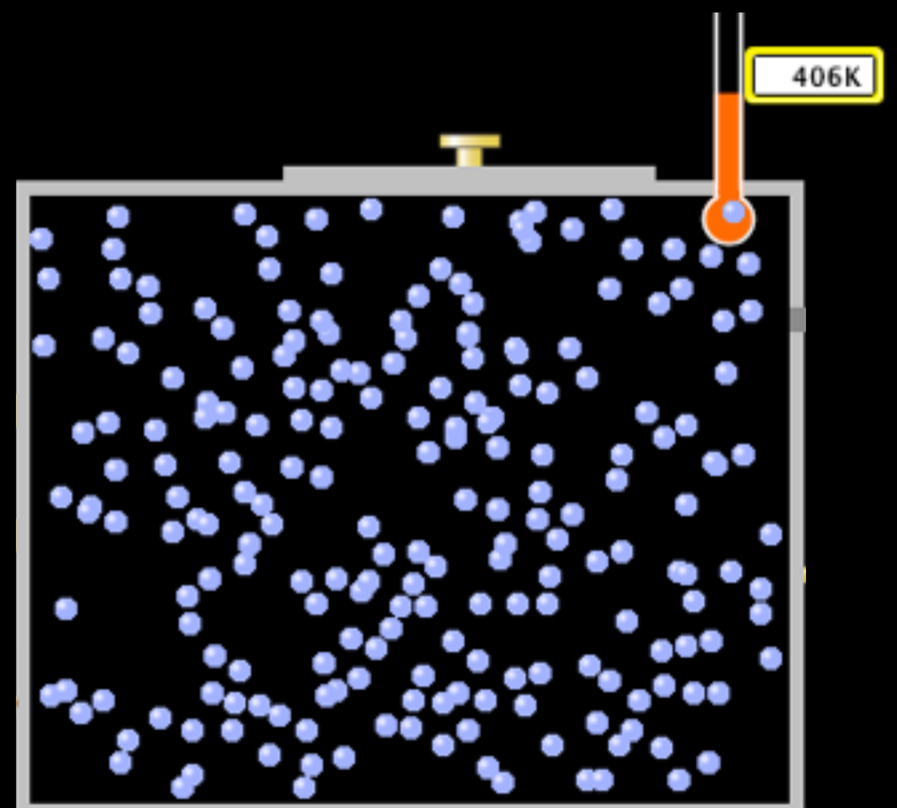
Volume (V) Pressure (p) Temperature (T)

If p is constant, what happen to V if we lower T?

(a) Volume goes down ↓

(b) Volume goes up ↑

(c) Volume stays the same



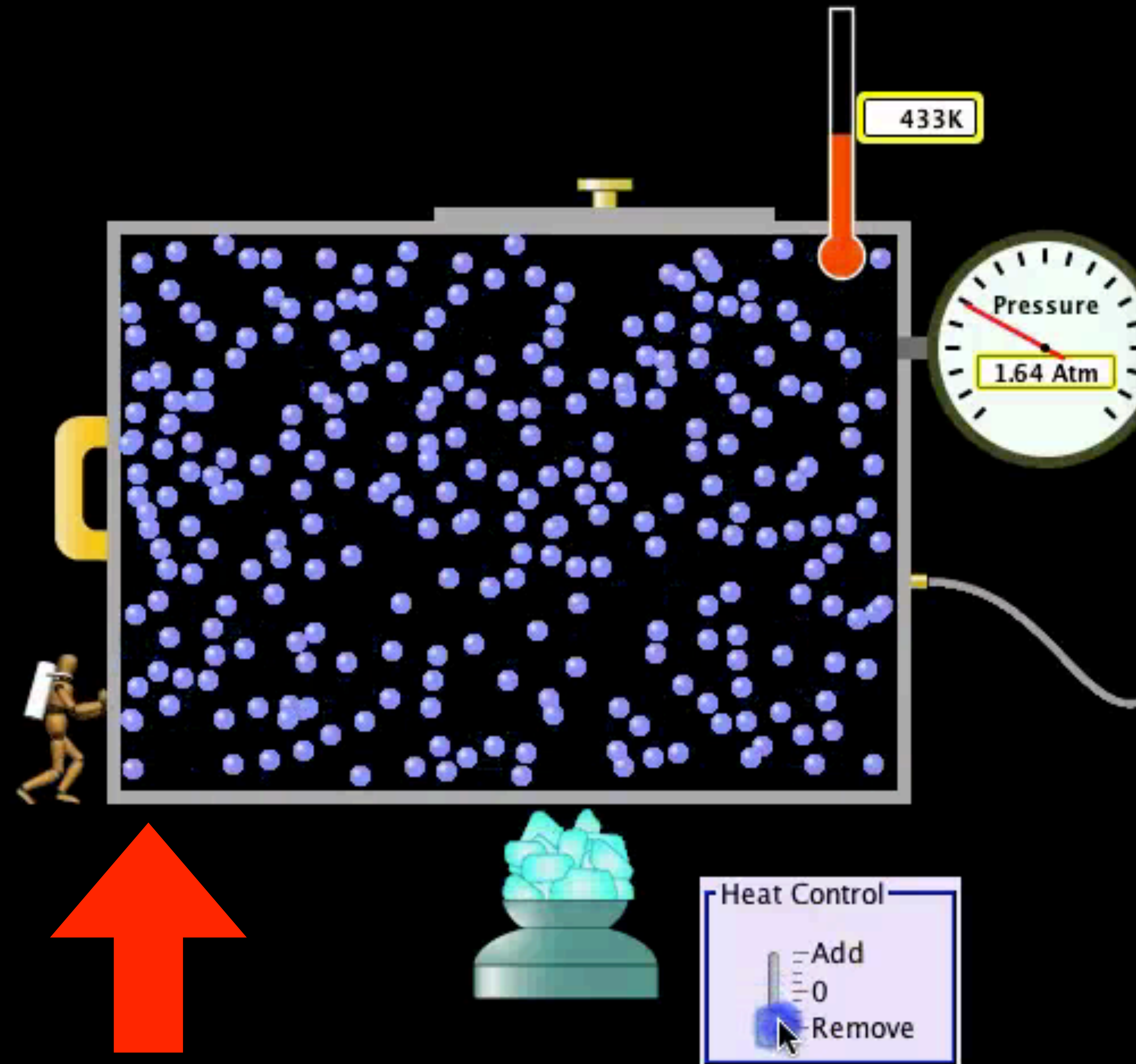
Ideal Gas Law

p is constant,

T goes down ↓

V ... ... goes down ↓

$$T \propto V$$



Ideal Gas Law

Volume (V) Pressure (p) Temperature (T)

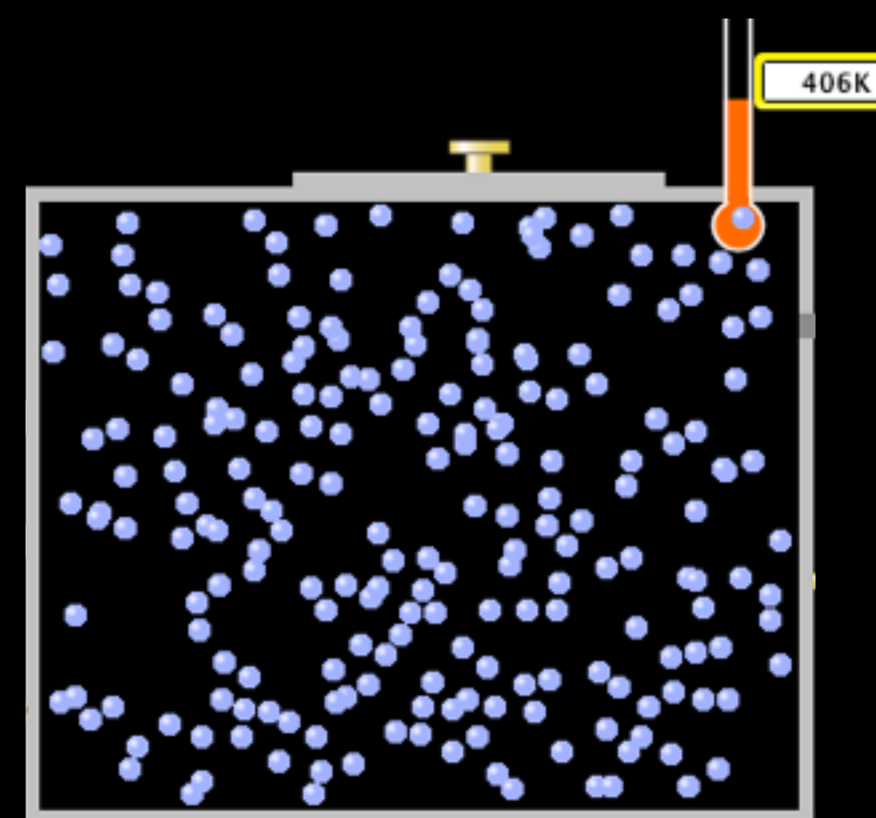
If p is constant, what happen to V if we lower T?

(a) Volume goes down ↓

$T \propto V$

(b) Volume goes up ↑

(c) Volume stays the same



Ideal Gas Law

$p \propto T$ $\qquad$ $p \propto \dfrac{1}{V}$ $\qquad$ $T \propto V$

Therefore: $pV \propto T$

What else affects p, V and T?

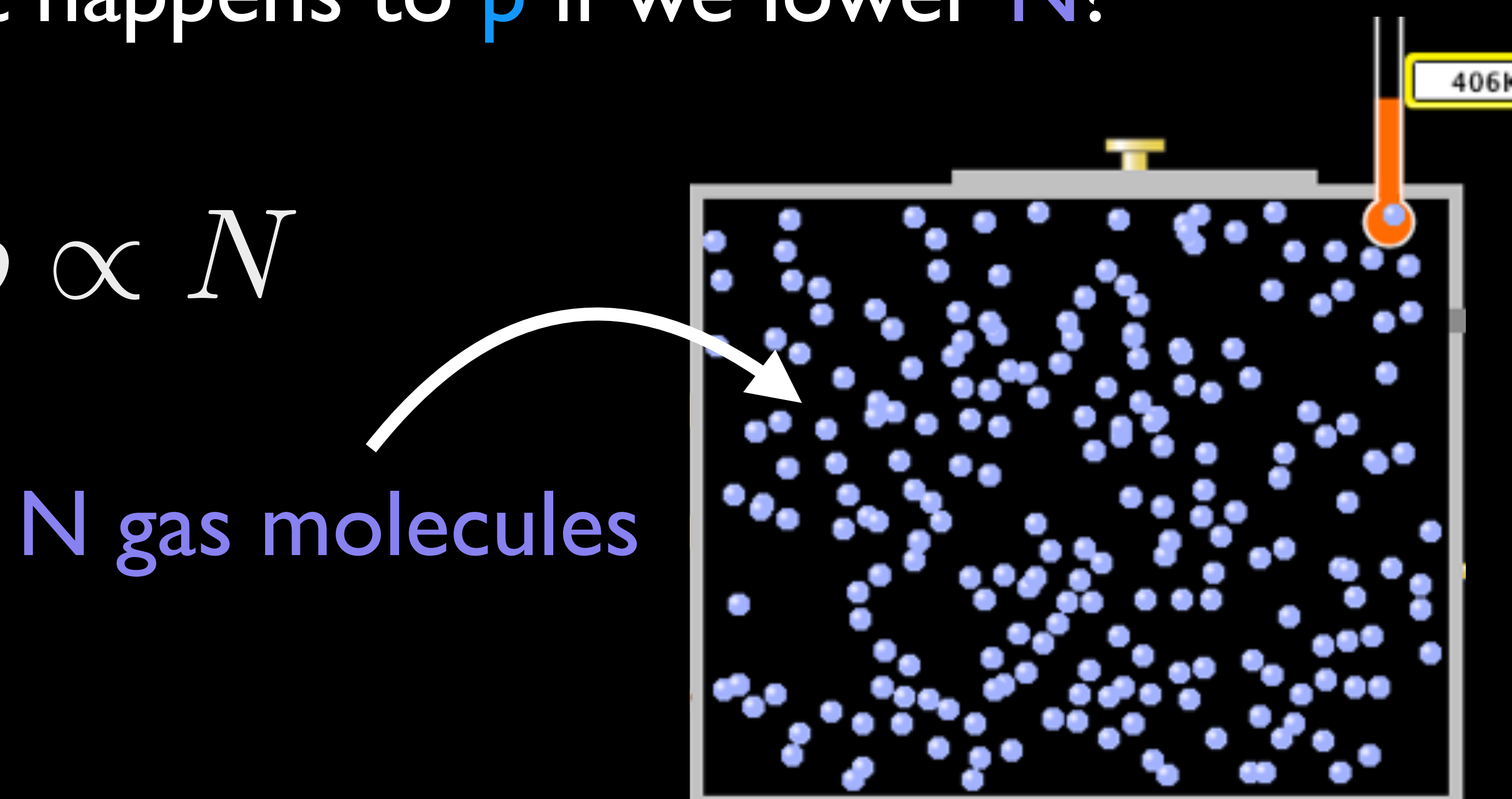
Bonus question:

If V and T are constant, what happens to p if we lower N?

(a) Pressure goes down $\quad p \propto N$

(b) Pressure goes up

(c) Pressure stays the same



Ideal Gas Law

$p \propto T$ $p \propto \frac{1}{V}$ $T \propto V$ $p \propto N$

Therefore: $$pV = NkT$$ ideal-gas law

N = # of gas molecules

$k = 1.38 \times 10^{-23}\,\mathrm{J/K}$

Boltzmann's constant

very large!

count # of moles: 1 mole, $N_A = 6.023 \times 10^{23}$ atoms

Avogadro's number

$$pV = nN_AkT = nRT$$

# of moles

$R = N_Ak = 8.314\,\mathrm{J/K \cdot mol}$

universal gas constant

Ideal Gas Law Ex.

What is the volume, V, of 1.00 mol of an ideal gas at T = $0^\circ\mathrm{C}$ and p = $101.3\,\mathrm{kPa}$?

$$R = 8.314\,\mathrm{J/K\cdot mol}$$

Ideal gas law: $pV = nRT$

$$V = \frac{nRT}{p} = \frac{(1.00\,\mathrm{mol})(8.314\,\mathrm{J/K\cdot mol})(273\,\mathrm{K})}{1.01\times 10^{5}\,\mathrm{Pa}}$$

$$= 22.4\times 10^{-3}\,\mathrm{m}^3$$

$$= 22.4\,\mathrm{L}$$

Ideal Gas Law — Quiz

An ideal gas has T = $109^\circ \mathrm{C}$ and p = $1.2 \times 10^4\,\mathrm{Pa}$.

How many gas molecules are in a cubic centimeter ($1\,\mathrm{cm}^3$) ?

$R = 8.314\,\mathrm{J/K \cdot mol} \qquad N_A = 6.023 \times 10^{23}$

(a) 7.98×10^{18} molecules

(b) 3.8×10^{-6} molecules

(c) 2.3×10^{18} molecules

(d) 1.3×10^{5} molecules

$$pV = nRT \;\rightarrow\; n = \frac{pV}{RT}$$

$$= \frac{(1.2 \times 10^4\,\mathrm{Pa})(0.01^3\,\mathrm{m}^3)}{(8.314\,\mathrm{J/K \cdot mol})(109 + 273\,\mathrm{K})}$$

$= 3.8 \times 10^{-6}$ moles

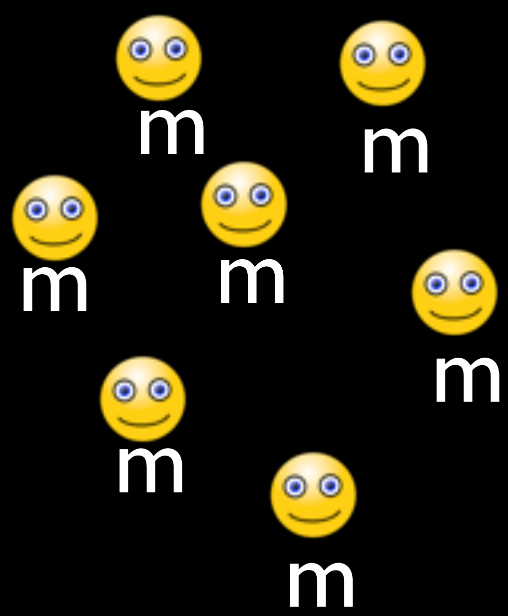
$N = 3.8 \times 10^{-6} \times 6.023 \times 10^{23}$

$= 2.27 \times 10^{18}$ molecules

Kinetic Theory of Gases

$pV = nRT$ is a very simple relation! ... why does it work?

Assume:

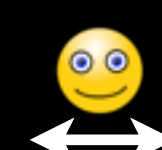


(1) Gas is made of identical molecules

- Mass, m
- Size ~ 0

nothing inside
(no internal structure)

~ True, if distance between gas molecules >> molecule size



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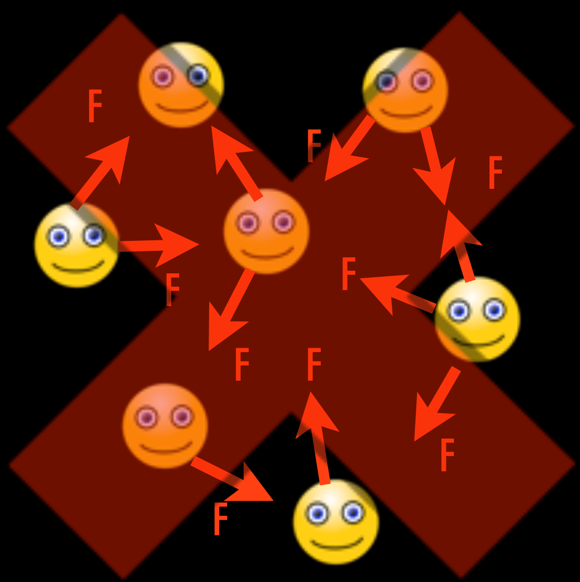
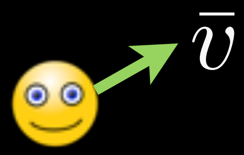


(II) No forces between molecules

only kinetic energy (K)



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

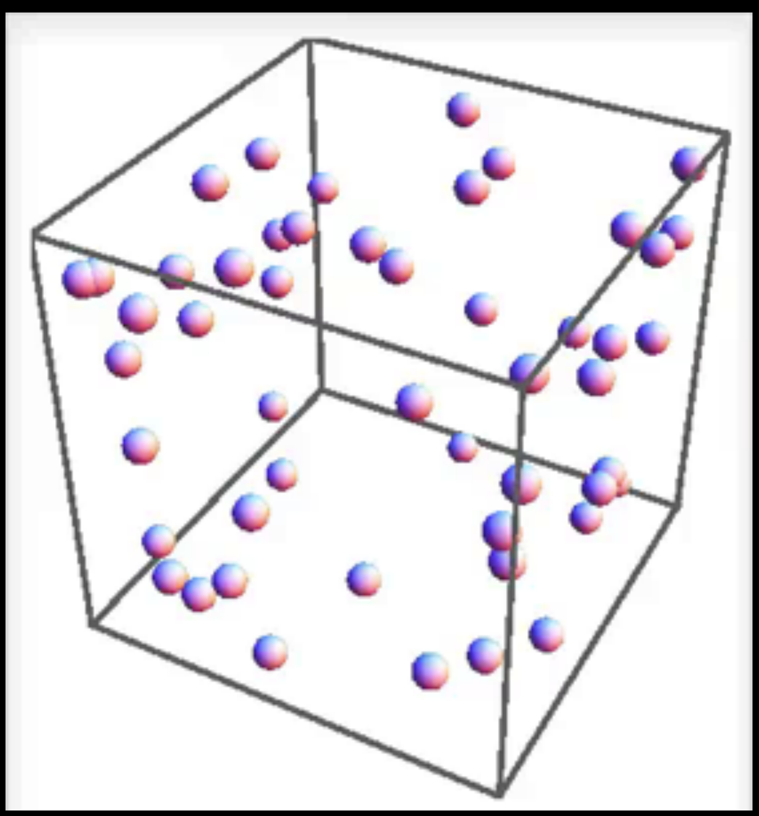
no potential energy (U)

Kinetic Theory of Gases

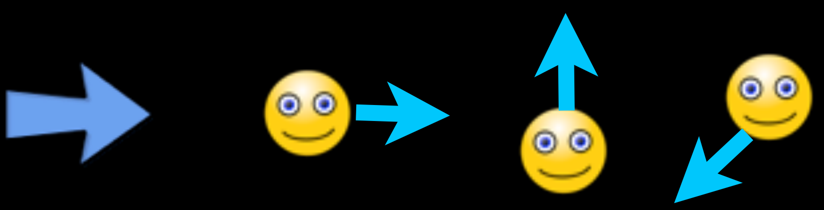
$pV = nRT$ is a very simple relation!

... why does it work?

Assume:



(III) molecules moves in random directions



speed $\not\propto$ direction

Kinetic Theory of Gases

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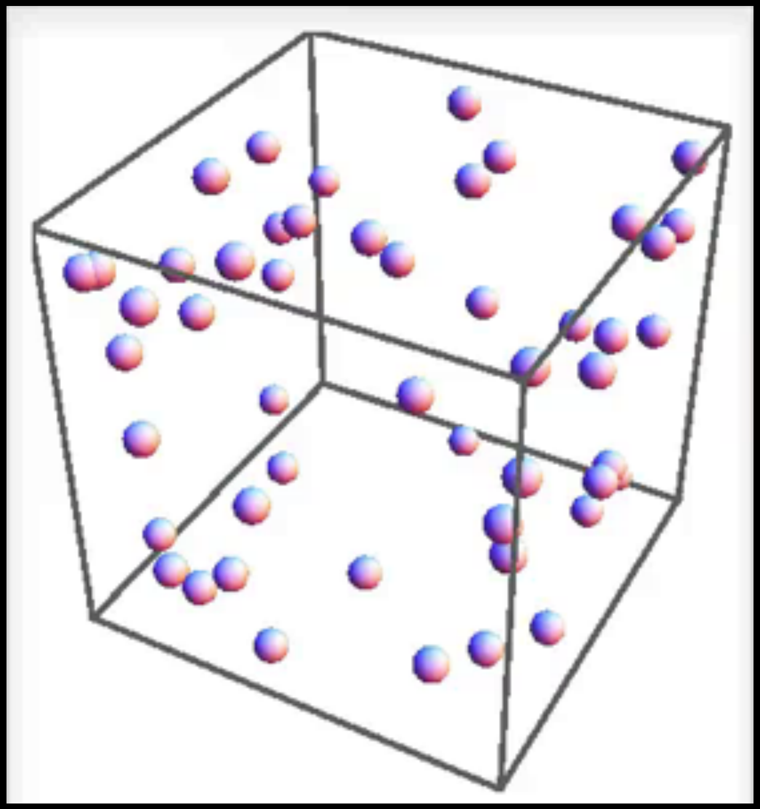
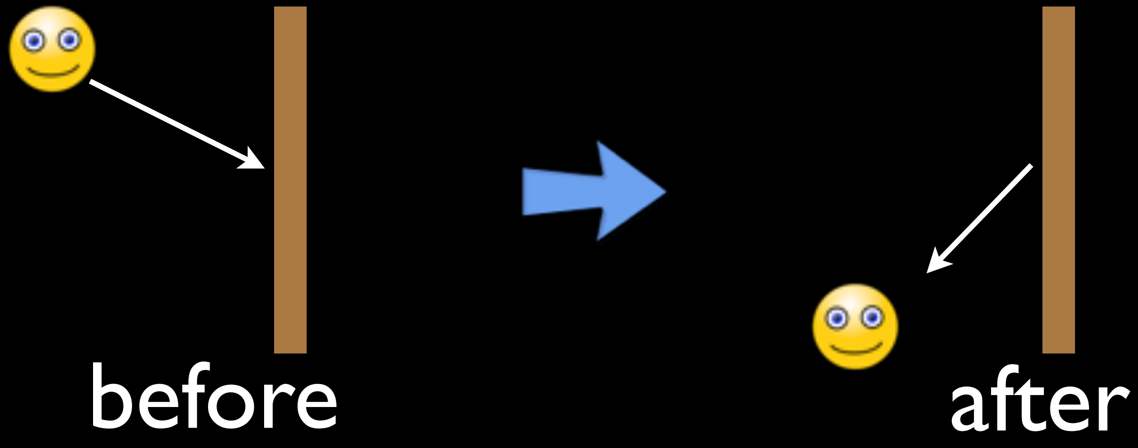


(IV) collisions with container wall are elastic

conserve molecule's momentum
energy

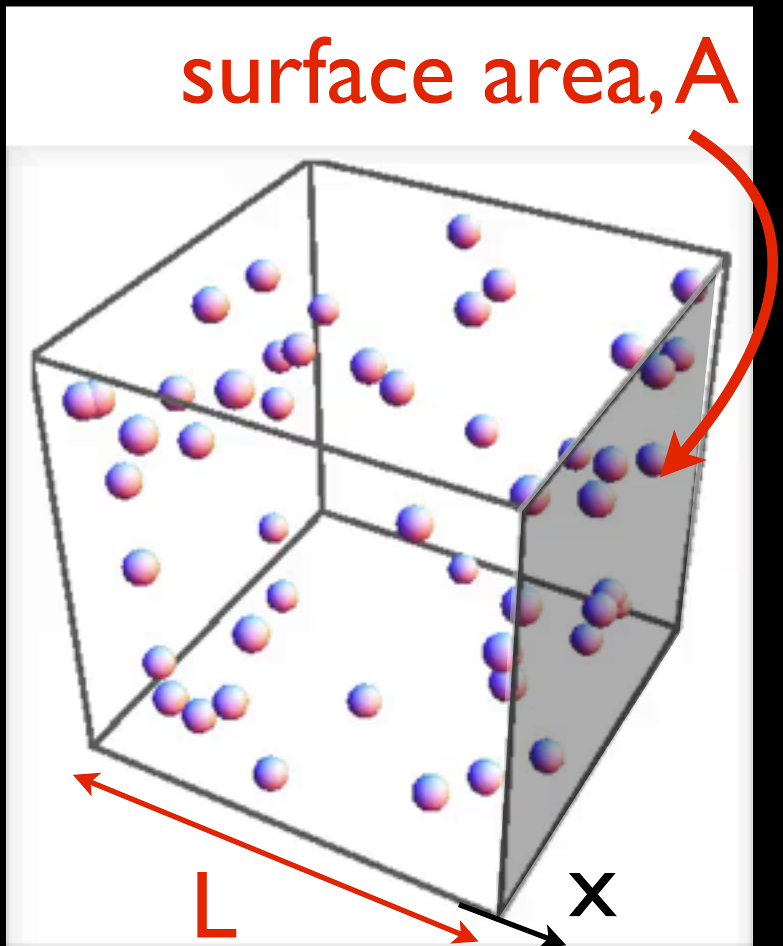


$$E_{\text{before}} = E_{\text{after}}$$

$$p_{\text{m,before}} = p_{\text{m,after}}$$

Kinetic Theory of Gases

N molecules in box



Molecules collide with wall with force, $\bar{F}_i$

many molecules → continuous F

gas pressure, $p = \dfrac{\bar{F}}{A}$ ← F?

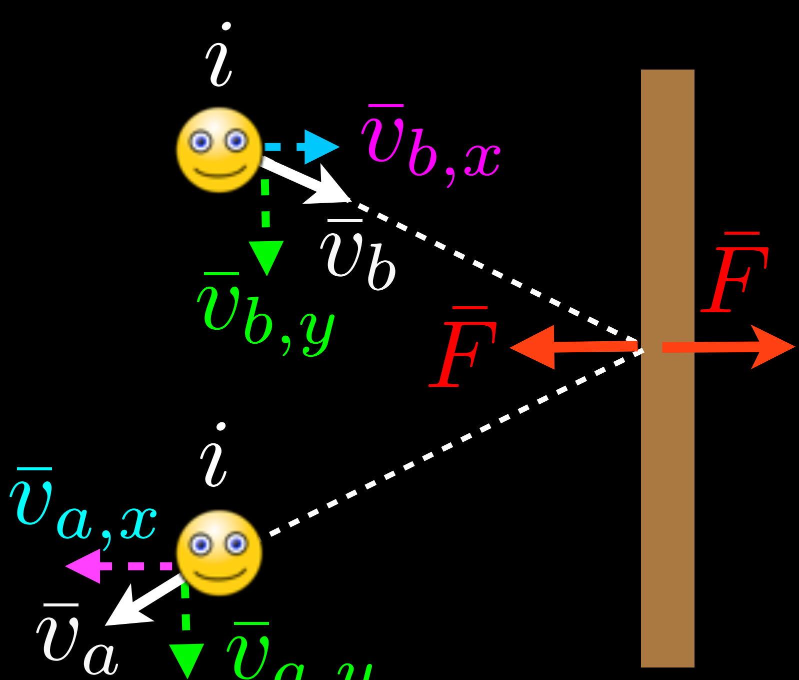
1 particle's collision with right wall:

Force, $\bar{F}$, only in x-direction: only $\bar{v}_x$ changes

velocity x-component

$\bar{v}_{a,y} = \bar{v}_{b,y}$

$\bar{v}_{a,x} = -\bar{v}_{b,x}$ → $\Delta v = 2v_x$



Newton's 2nd law for particle *i*

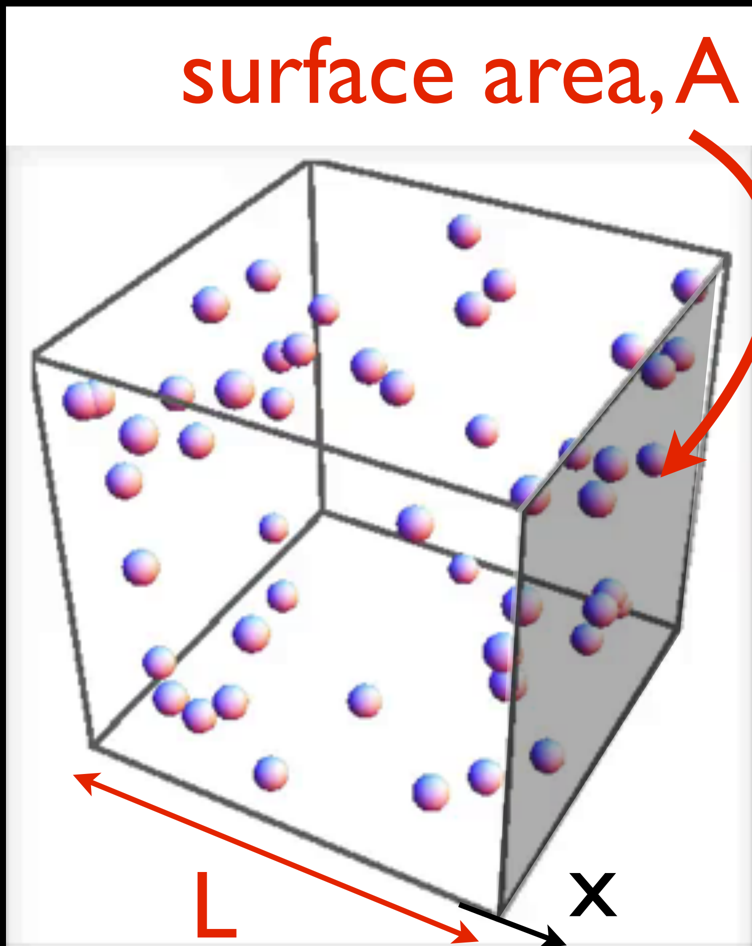
$$\bar{F}_i = \frac{\Delta \bar{p}_{mi}}{\Delta t_i}$$

change in momentum, $\Delta p_{mi} = m\Delta v_i$

time between collisions, $\Delta t_i = 2L/v_{x,i}$

Kinetic Theory of Gases

N molecules in box



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F?

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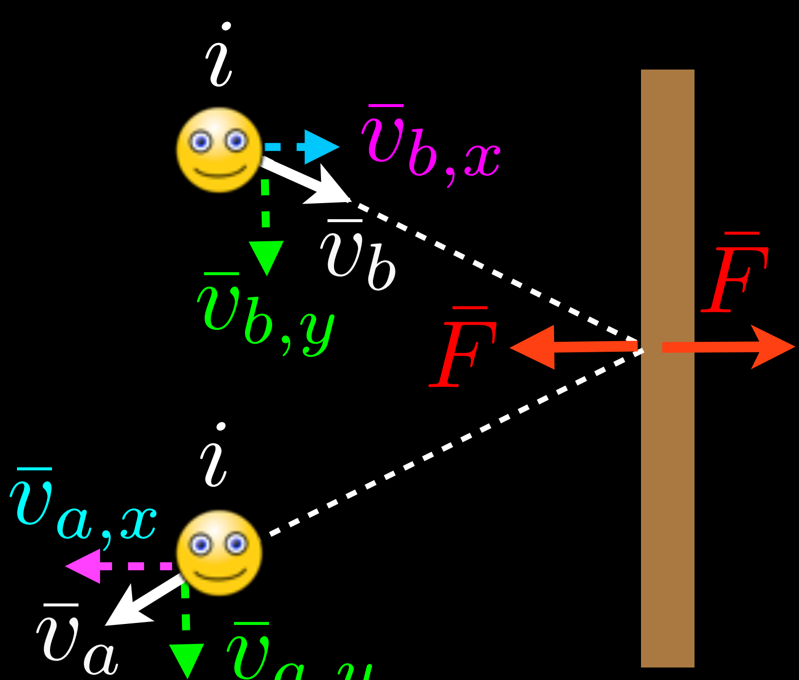
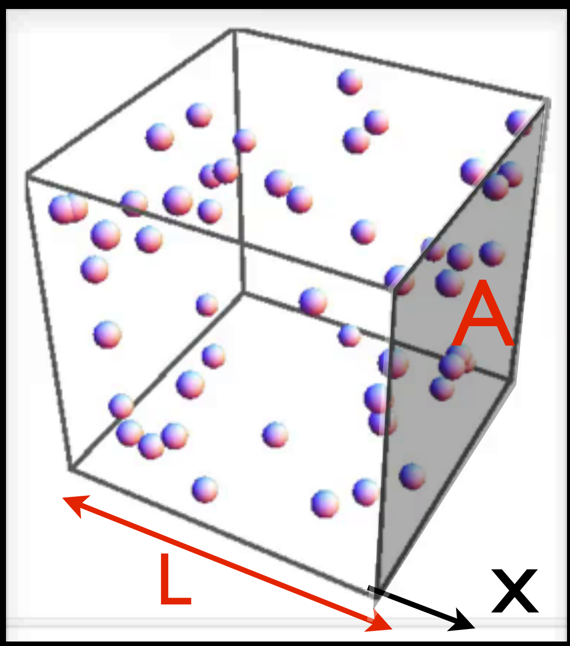


Newton's 2nd law for particle *i*

$$\bar{F}_i = \frac{\Delta \bar{p}_{mi}}{\Delta t_i} = \frac{2mv_{x,i}}{2L/v_{x,i}} = \frac{mv_{x,i}^2}{L}$$

Kinetic Theory of Gases

N molecules in box



Total force on wall: $\bar{F} = \sum \bar{F}_i$

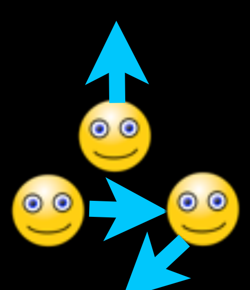
$$p = \frac{\bar{F}}{A} = \frac{\sum \bar{F}_i}{A} = \frac{\sum m v_{x,i}^2 / L}{A} = \frac{m \sum v_{x,i}^2}{AL}$$

volume, V

$$= \frac{N}{N} \frac{m \sum v_{x,i}^2}{V} = \frac{mN}{V} \frac{\sum v_{x,i}^2}{N} = \frac{mN}{V} \bar{v_x^2}$$

= 1

average v_x^2 of all molecules $= \bar{v_x^2}$



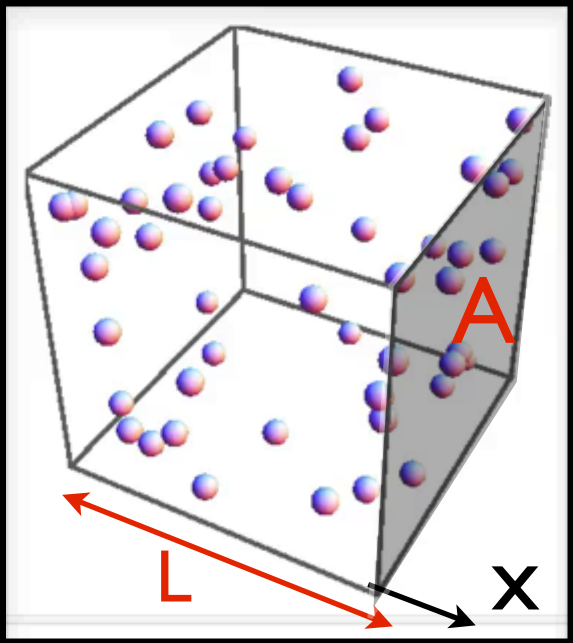
But molecules move in random directions (III) : $\bar{v_x^2} = \bar{v_y^2} = \bar{v_z^2}$

Average speed: $\bar{v^2} = \bar{v_x^2} + \bar{v_y^2} + \bar{v_z^2} = 3\bar{v_x^2} \rightarrow \bar{v_x^2} = \frac{1}{3}\bar{v^2}$

$$\Rightarrow p = \frac{mN}{3V}\bar{v^2}$$

Kinetic Theory of Gases

N molecules in box



$$p = \frac{mN}{3V}\bar{v^2} \quad \Rightarrow \quad pV = \frac{2}{2}\frac{mN}{3}\bar{v^2}$$

= 1

$$= \frac{2}{3}N\left(\frac{1}{2}m\bar{v^2}\right)$$

Average kinetic energy of molecule

But... ideal gas law: $pV = NkT$

$$kT = \frac{2}{3}\left(\frac{1}{2}m\bar{v^2}\right)$$

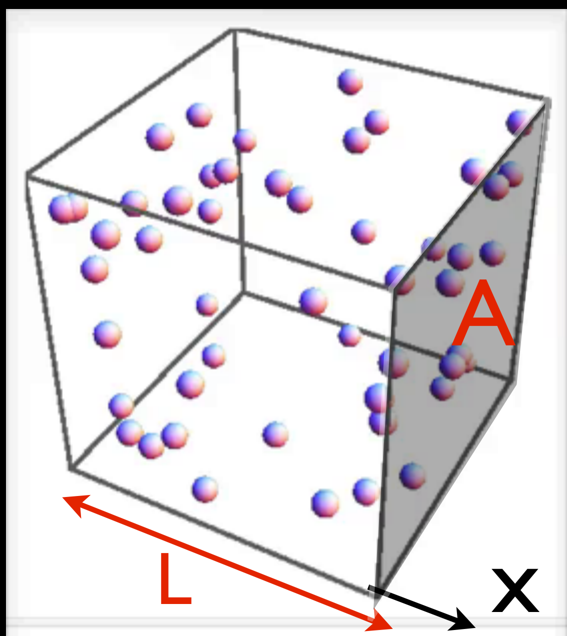
macroscopic property (Temperature, T)

microscopic property (molecule's energy)

Laws of mechanics give us the ideal gas law!

Kinetic Theory of Gases

N molecules in box



$$p = \frac{mN}{3V}\overline{v^2} \quad \Rightarrow \quad pV = \frac{2}{2}\frac{mN}{3}\overline{v^2}$$

= 1

$$= \frac{2}{3}N\left(\frac{1}{2}m\overline{v^2}\right)$$

Average kinetic energy of molecule

But... ideal gas law: $pV = NkT$

$$kT = \frac{2}{3}\left(\frac{1}{2}m\overline{v^2}\right)$$

macroscopic property (Temperature, T)

microscopic property (molecule's energy)

$$\Rightarrow \boxed{\frac{3}{2}kT = \frac{1}{2}m\overline{v^2}}$$

T measures average K of molecules

Kinetic Theory of Gases Ex.

Find the average kinetic energy of a molecule at 20° C.

Average kinetic energy: $\bar{K} = \frac{1}{2}m\bar{v^2} \quad = \frac{3}{2}kT$

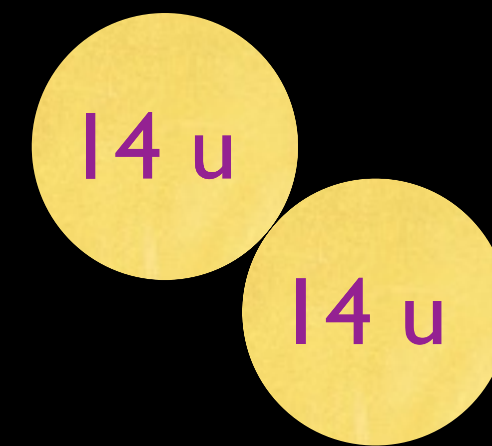
$$= \frac{3}{2}(1.38 \times 10^{-23}\,\mathrm{J/K})(293\,\mathrm{K})$$

$$= 6.07 \times 10^{-21}\,\mathrm{J}$$

Kinetic Theory of Gases Ex.

... what is the speed of a nitrogen molecule ($\mathrm{N_2}$) with this energy?

$$1u = 1.66 \times 10^{-27}\,\mathrm{kg}$$



$$m = 2(14\,u)(1.66 \times 10^{-27}\,\mathrm{kg/u})$$

$$= 4.65 \times 10^{-26}\,\mathrm{kg}$$

$$\bar{K} = \frac{1}{2} m\overline{v^2} \quad \Rightarrow \quad v = \sqrt{\frac{2K}{m}} = \sqrt{\frac{2(6.07 \times 10^{-21}\,\mathrm{J})}{4.65 \times 10^{-26}\,\mathrm{kg}}}$$

$$= 511\,\mathrm{m/s}$$

Kinetic Theory of Gases Quiz

A 5.0 litre gas tank holds 1.4 moles of helium (He) and 0.70 moles of oxygen (O_2) at T = 260 K.

Find the TOTAL (translational) kinetic energy of the gas.

$$N_A = 6.023 \times 10^{23}$$

$$k = 1.38 \times 10^{-23}\,\mathrm{J/K}$$

$$1u = 1.66 \times 10^{-27}\,\mathrm{kg}$$

$$m_{\mathrm{He}} = 4u$$

$$m_{\mathrm{O}} = 16u$$

(a) $6.8\,\mathrm{kJ}$

(b) $6.1\,\mathrm{kJ}$

(c) $7.6\,\mathrm{kJ}$

(d) $8.3\,\mathrm{kJ}$

Kinetic Theory of Gases Quiz

A 5.0 litre gas tank holds 1.4 moles of helium (He) and 0.70 moles of oxygen (O_2) at T = 260 K.

Find the TOTAL (translational) kinetic energy of the gas.

(a) $6.8\,\mathrm{kJ}$

K for one molecule: $K = \frac{3}{2}kT$

$$\frac{3}{2}(1.38 \times 10^{-23}\,\mathrm{J/K})(260\,\mathrm{K})$$

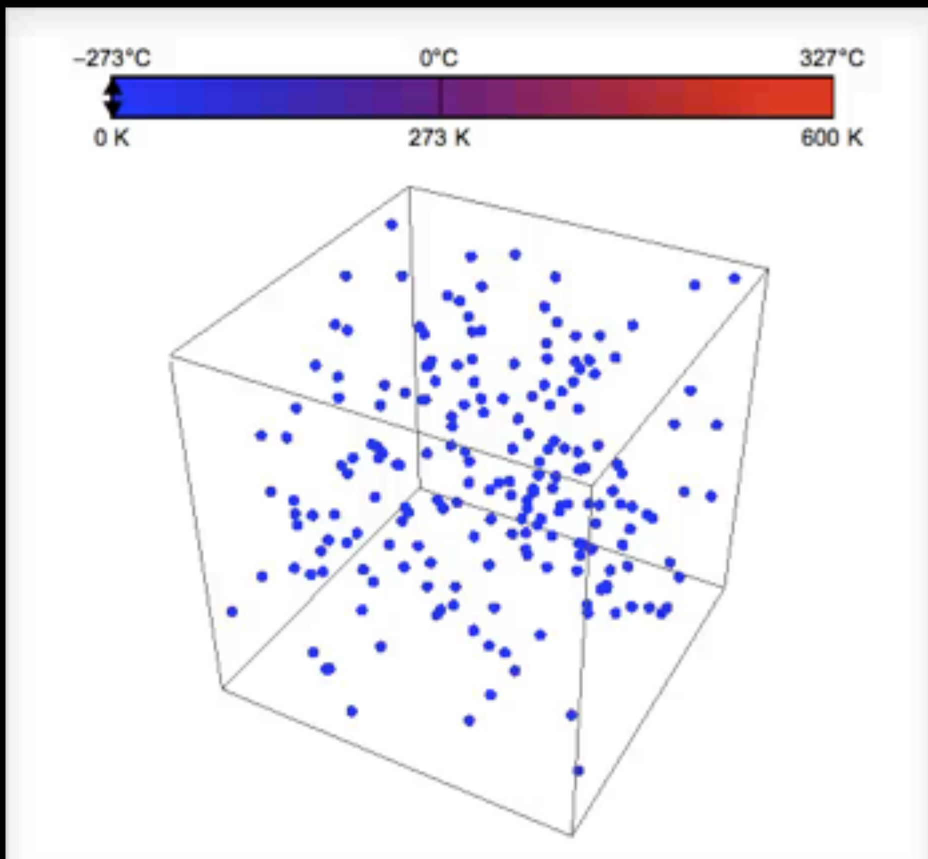
$$= 5.38 \times 10^{-21}\,\mathrm{J}$$

All molecules:

$$(\underbrace{1.4 \times 6.023 \times 10^{23}}_{\text{He}} + \underbrace{0.7 \times 6.023 \times 10^{23}}_{O_2}) \times 5.38 \times 10^{-21}\,\mathrm{J}$$

$$= 6.8\,\mathrm{kJ}$$

Molecule speeds

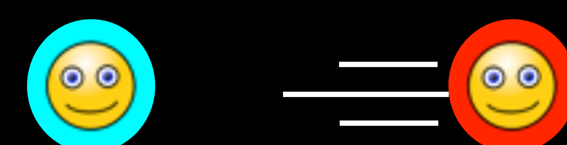


$$\frac{3}{2}kT = \frac{1}{2}m\overline{v^2} \quad \Rightarrow \quad v_{\rm th} = \sqrt{\frac{3kT}{m}}$$

thermal speed

Typical molecular speed

but ... what are the range of speeds?



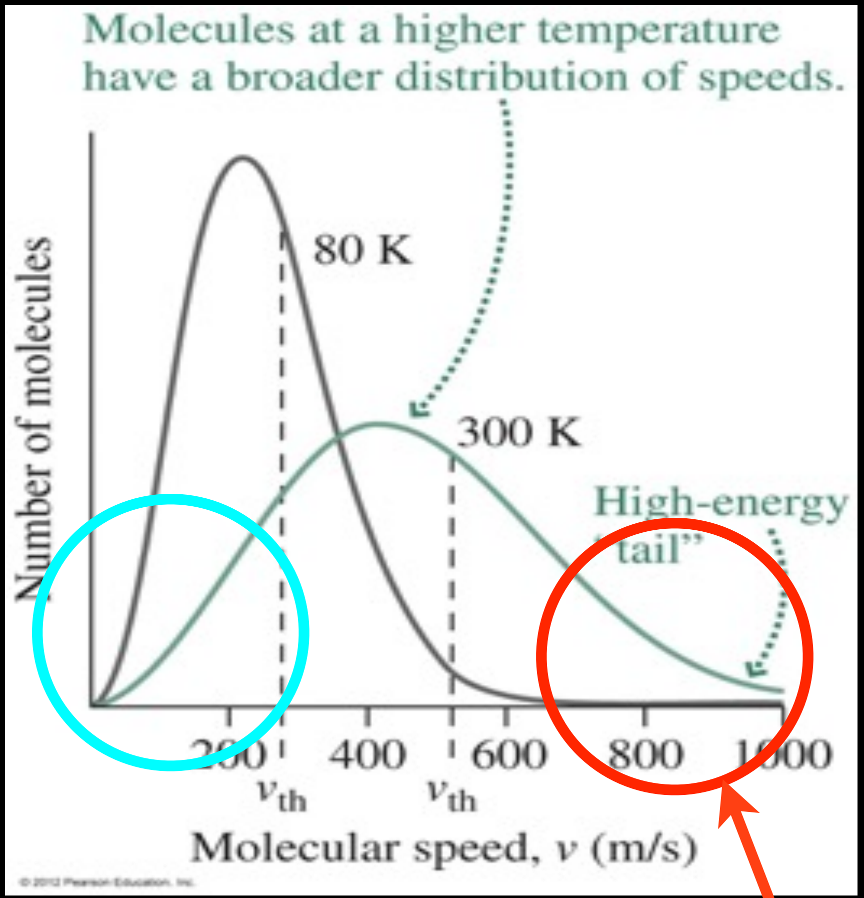
$v_{\rm min}$ $v_{\rm max}$

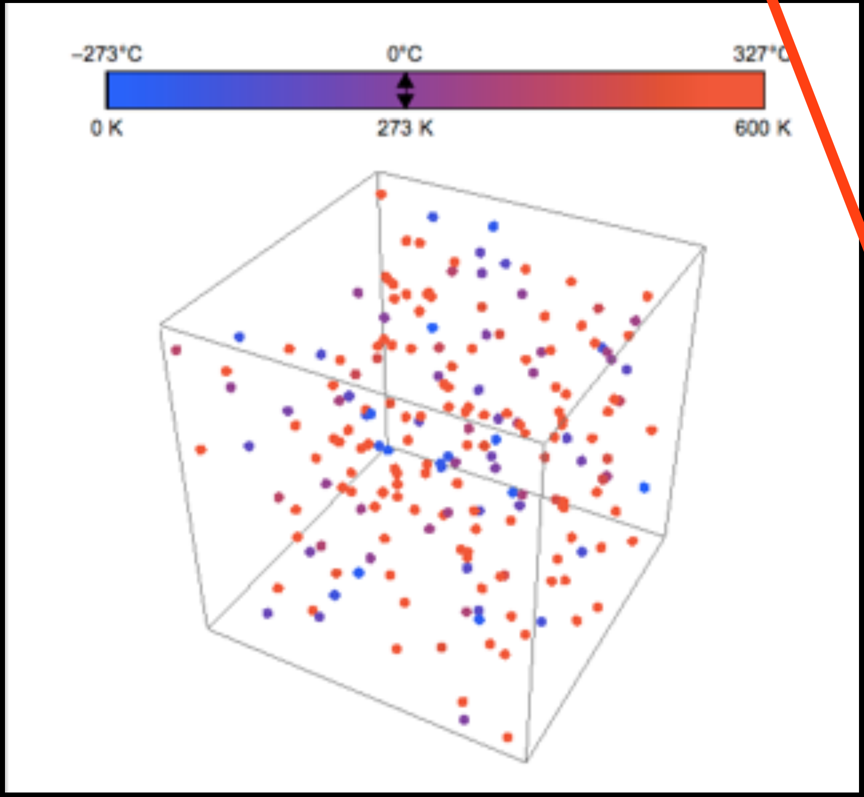
As T ↑

Typical speed ↑

But not all molecules have the same speed

Molecule speeds





Maxwell-Boltzmann distribution:

range of molecule speeds

peak at typical speed, $v_{\rm th}$

peak position depends on T

Higher T

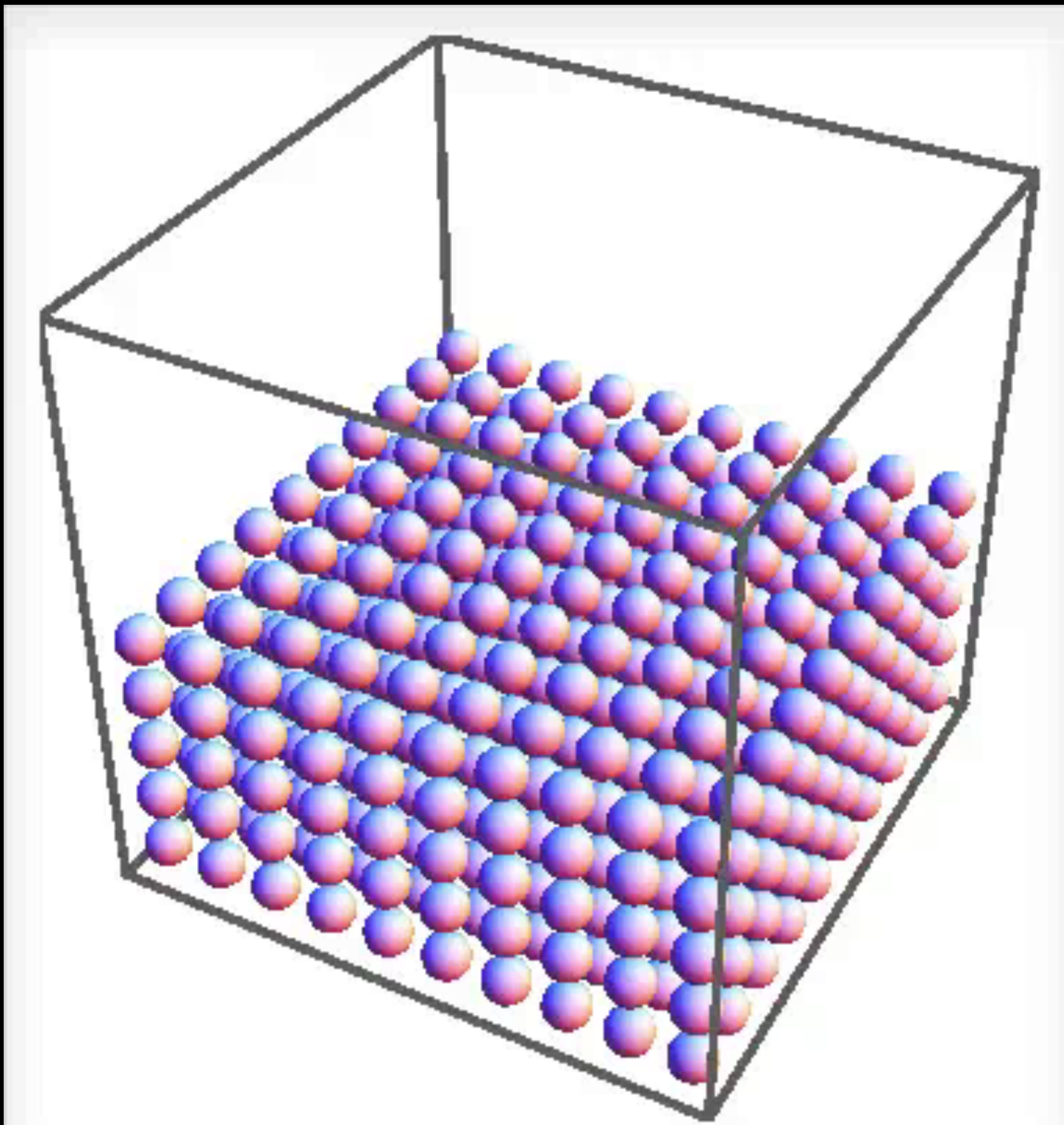
→ Higher $v_{\rm th}$

→ Larger range: more molecules at high and low speeds

reaction rates faster at high T

foods keep longer at low T

Phase changes



++ heat energy

T increases...

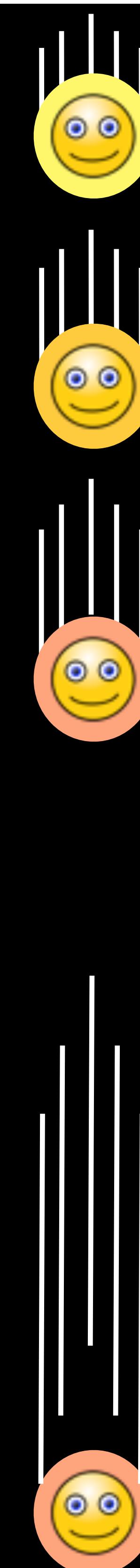
... molecules move faster
(++ kinetic energy)

But, if we add more heat

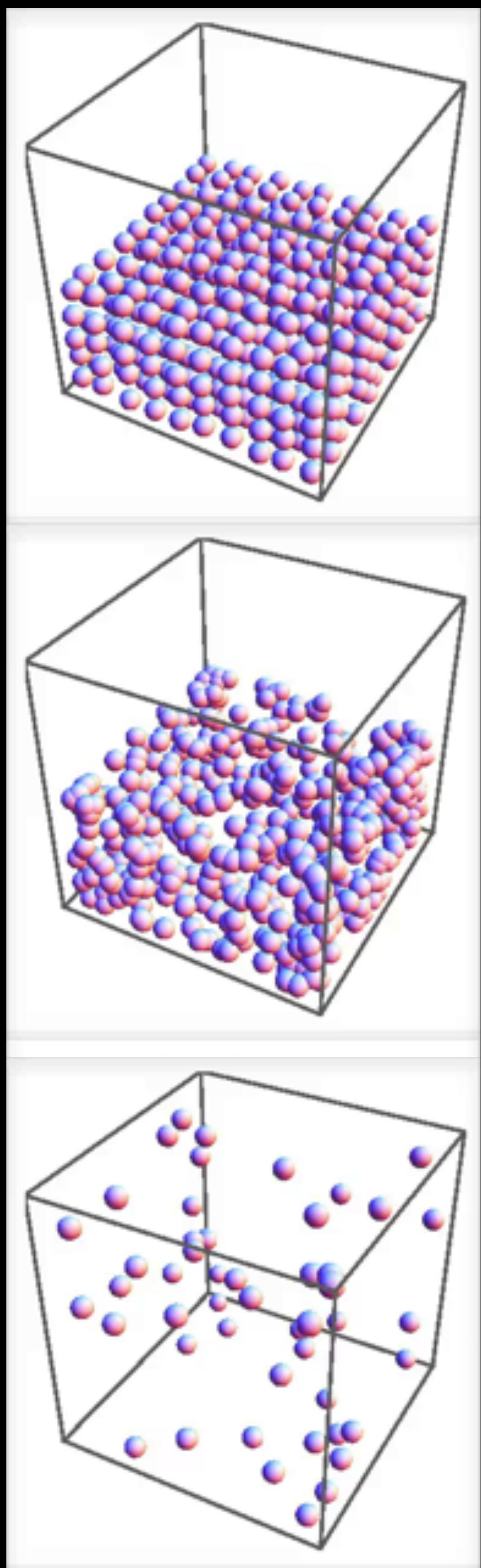
suddenly molecules
move freely ...

... at the same T (and v)

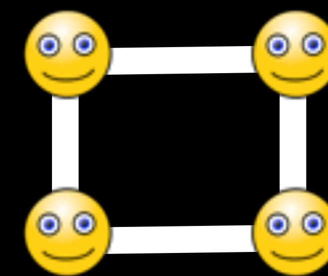
This is a phase change



Phase changes

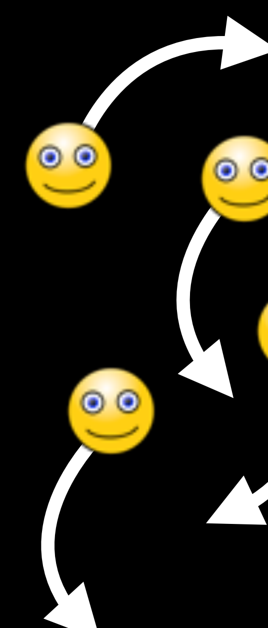


Solid



In a phase change

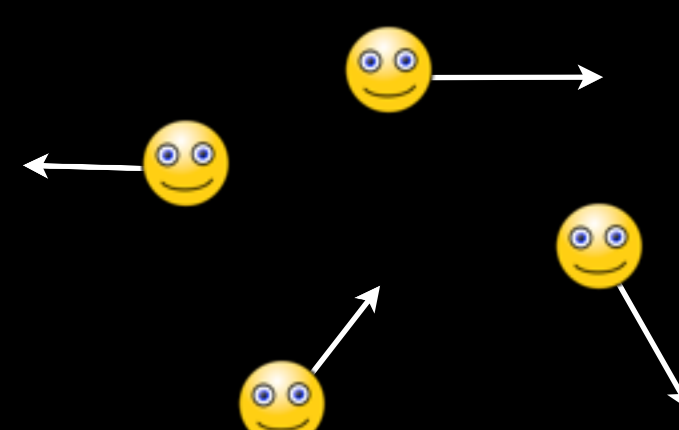
liquid



Energy is used to break molecule bonds

Temperature stays constant

gas

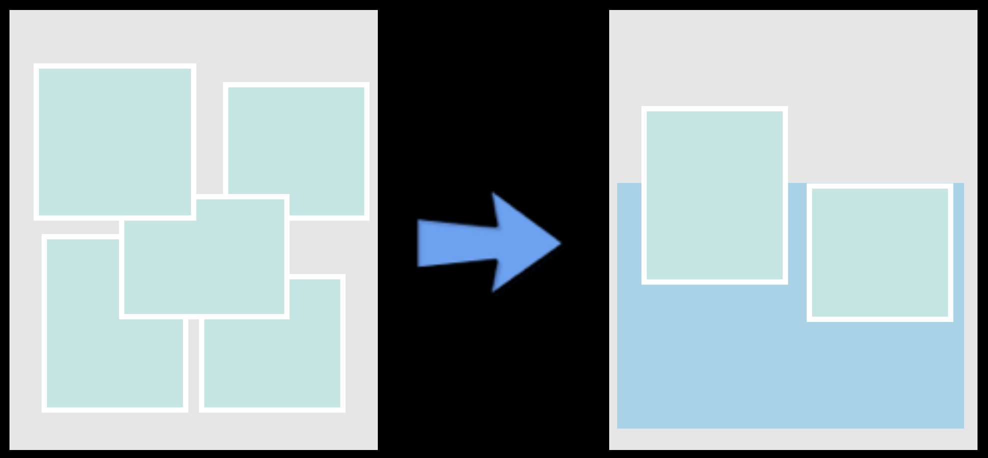


Phase changes

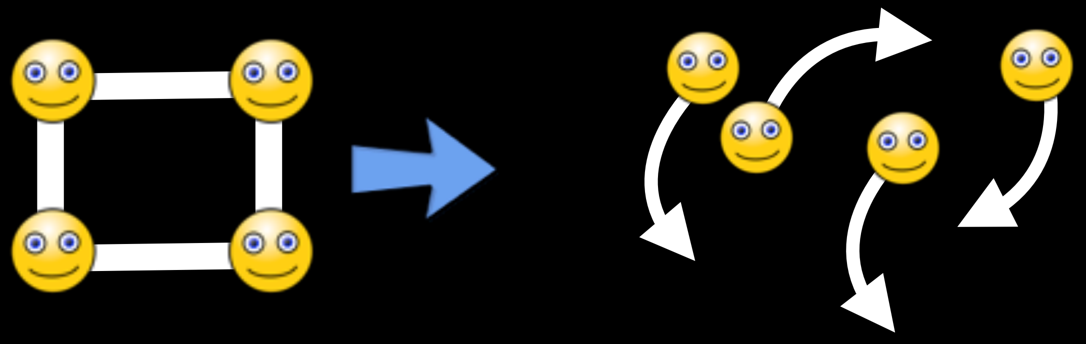
Quiz

A glass is full of ice at $0^\circ\mathrm{C}$

After 1 hour, half the ice has melted. Is the temperature, T....



Heat energy goes into breaking molecular bonds



(A) $< 0^\circ\mathrm{C}$

(B) $> 0^\circ\mathrm{C}$

(C) $0^\circ\mathrm{C}$

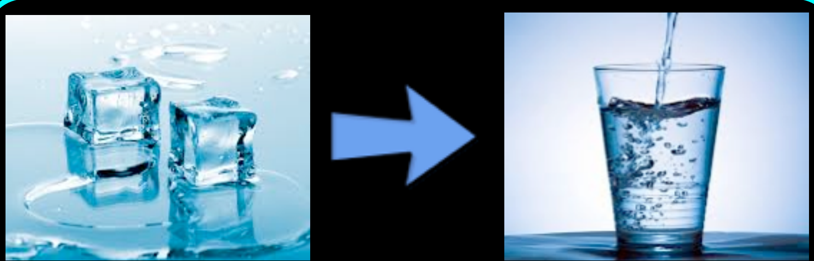
(D) Depends on the glass

while there is ice, all energy used in bond breaking.

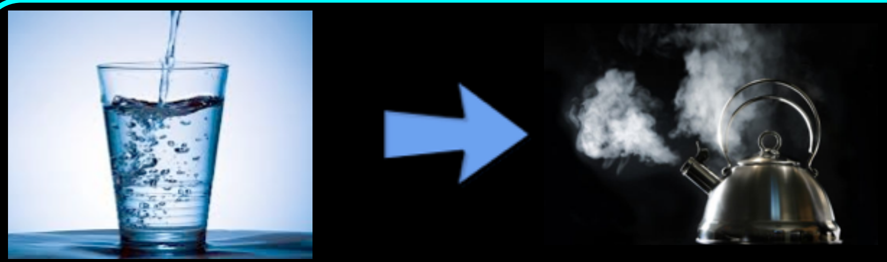
no energy raises molecule's kinetic energy (temperature)

Phase changes

Energy / mass needed for a phase change: heat of transformation, L
[J/kg]



Solid-liquid change:
heat of fusion, L_f



Liquid-gas change:
heat of vaporization, L_v

Solid-gas change:
heat of sublimation

$$Q = Lm$$

(heat of transformation)

Energy needed to change phase of mass, m

M

Phase changes

Solid-gas change:

heat of sublimation

CO has a low temperature for sublimation

(dry ice)

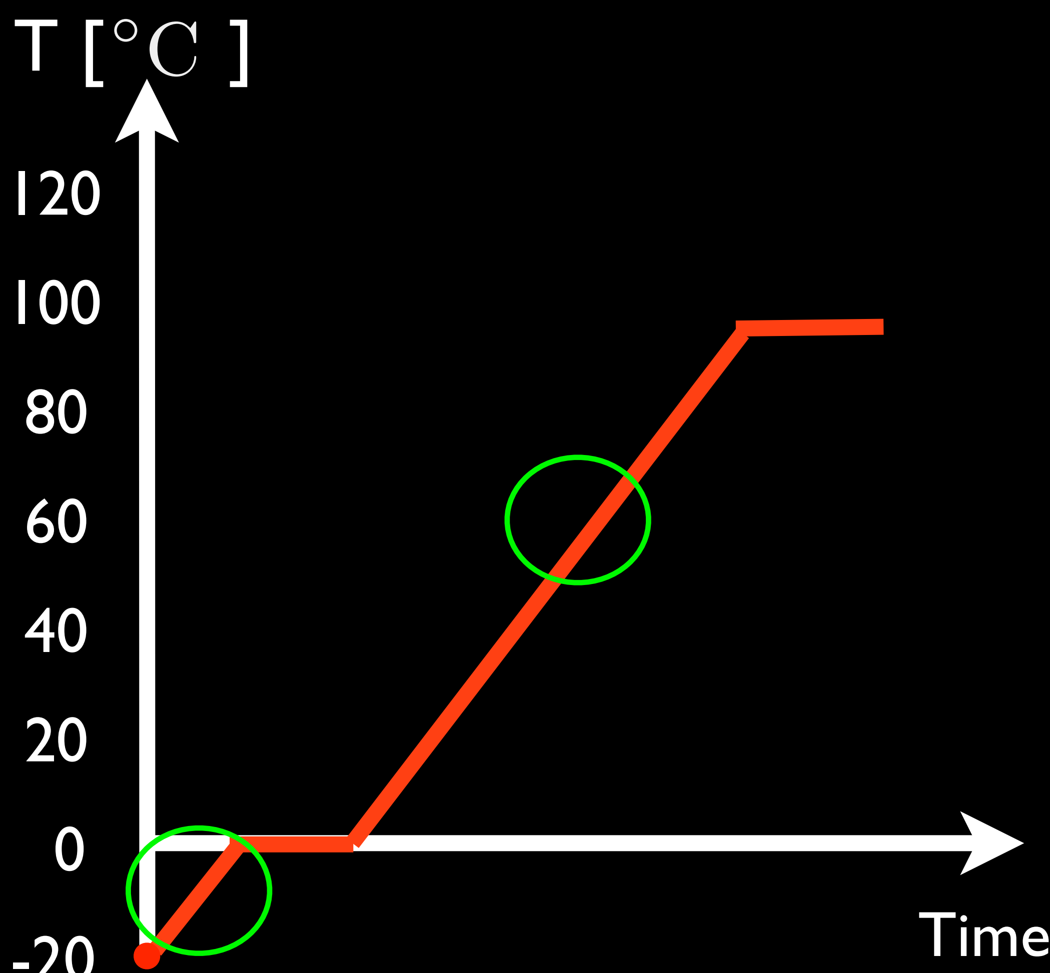
Phase changes

Table 17.1 Heats of Transformation (at Atmospheric Pressure)

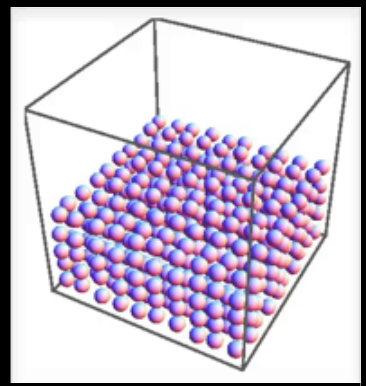
Substance	Melting Point (K)	L_f (kJ/kg)	Boiling Point (K)	L_v (kJ/kg)
Alcohol, ethyl	159	109	351	879
Copper	1357	205	2840	4726
Lead	601	24.7	2013	858
Mercury	234	11.3	630	296
Oxygen	54.8	13.8	90.2	213
Sulfur	388	53.6	718	306
Water	273	334	373	2257
Uranium dioxide	3120	259	3815	1533

Phase changes

When heating ice, what happens to T?



Start at $-20^{\circ}\mathrm{C}$.



Temperature increases to $0^{\circ}\mathrm{C}$

@ $0^{\circ}\mathrm{C}$, ice begins to melt (phase transition)

$L_f m$

T = constant

When all ice is water, T increases again:

$c_{\mathrm{water}} > c_{\mathrm{ice}}$ water heats more slowly than ice: smaller gradient

specific heat capacity

@ $100^{\circ}\mathrm{C}$, water becomes steam

$\xrightarrow{L_v m}$

T = constant

Phase changes

Quiz

How much energy does it take to melt a 45 g ice cube?

$$L_f = 334\,\mathrm{kJ/kg}$$

(a) $22\,\mathrm{kJ}$

(b) $15\,\mathrm{kJ}$

(c) $0.1\,\mathrm{kJ}$

(d) $15480\,\mathrm{kJ}$

$$Q = L_f m$$

$$= (334\,\mathrm{kJ/kg})(0.045\,\mathrm{kg})$$

$$= 15.03\,\mathrm{kJ}$$

Phase changes

Ex.

200 g of ice at $-10^\circ\mathrm{C}$ are added to 1.0 kg of water at $15^\circ\mathrm{C}$

Is there enough ice to cool the water to $0^\circ\mathrm{C}$?

Energy removed (Q_1):

Energy to raise T to $0^\circ\mathrm{C}$ + Energy to melt ice

$$m_{\text{ice}} c_{\text{ice}} \Delta T_{\text{ice}} \qquad m_{\text{ice}} L_f$$

$$(0.20\,\mathrm{kg})(2.05\,\mathrm{kJ/kg\cdot K})(10\,\mathrm{K}) + (0.20\,\mathrm{kg})(344\,\mathrm{kJ/kg})$$

$$Q_1 = 4.1\,\mathrm{kJ} + 66.8\,\mathrm{kJ} = 70.9\,\mathrm{kJ}$$

$Q_1 > Q_2$

Yes!

To cool water: $Q_2 = m_{\text{water}} c_{\text{water}} \Delta T_{\text{water}}$

$$= (1.0\,\mathrm{kg})(4.184\,\mathrm{kJ/kg\cdot K})(15\,\mathrm{K}) = 62.8\,\mathrm{kJ}$$

Phase changes

Quiz

How much heat must you add to vapourise (turn to steam) 2.0 g of water at 0° C?

$$l_f = 80\,\mathrm{cal/g}$$

$$l_v = 539\,\mathrm{cal/g}$$

$$c = 1.0\,\mathrm{cal/g \cdot K}$$

watch units!

(a) $1100\,\mathrm{cal}$

(b) $1100\,\mathrm{kcal}$

(c) $1200\,\mathrm{cal}$

(d) $1300\,\mathrm{cal}$

Phase changes Quiz

How much heat must you add to vapourise (turn to steam) 2.0 g of water at 0° C?

(a) $1100\,\mathrm{cal}$

(b) $1100\,\mathrm{kcal}$

(c) $1200\,\mathrm{cal}$

(d) $1300\,\mathrm{cal}$

$$Q = mc\Delta T + mL_v$$

$$= (2.0\,\mathrm{g})(1.0\,\mathrm{cal/g\cdot K})(100\,K) + (2.0\,\mathrm{g})(539\,\mathrm{cal/g})$$

$$= 1278\,\mathrm{cal}$$

Phase diagrams

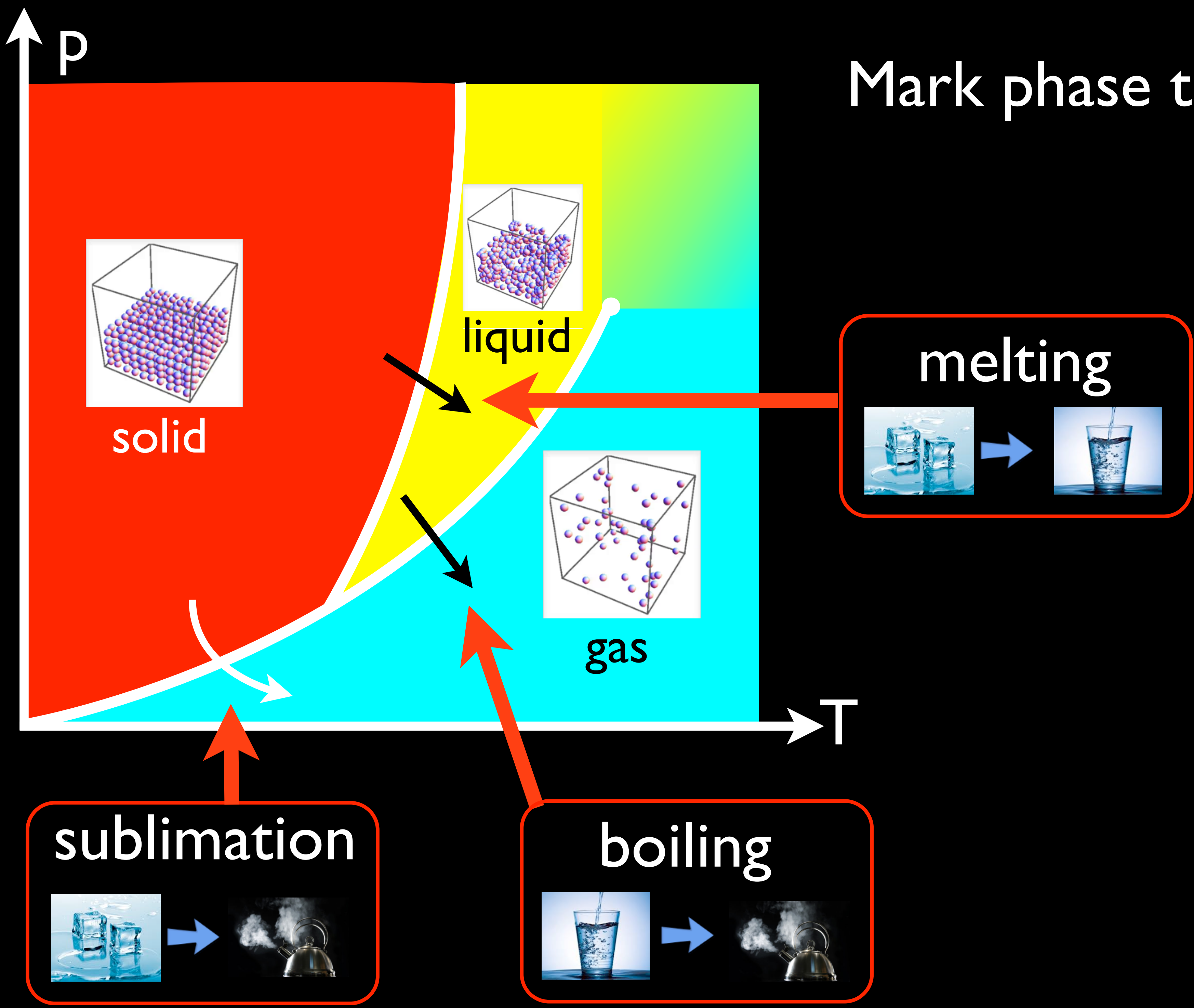
Phase changes occur at a given T ... ... and a given p

If p $\downarrow$ $\Rightarrow$ $T_{\mathrm{phase}} \downarrow$

Phase diagrams

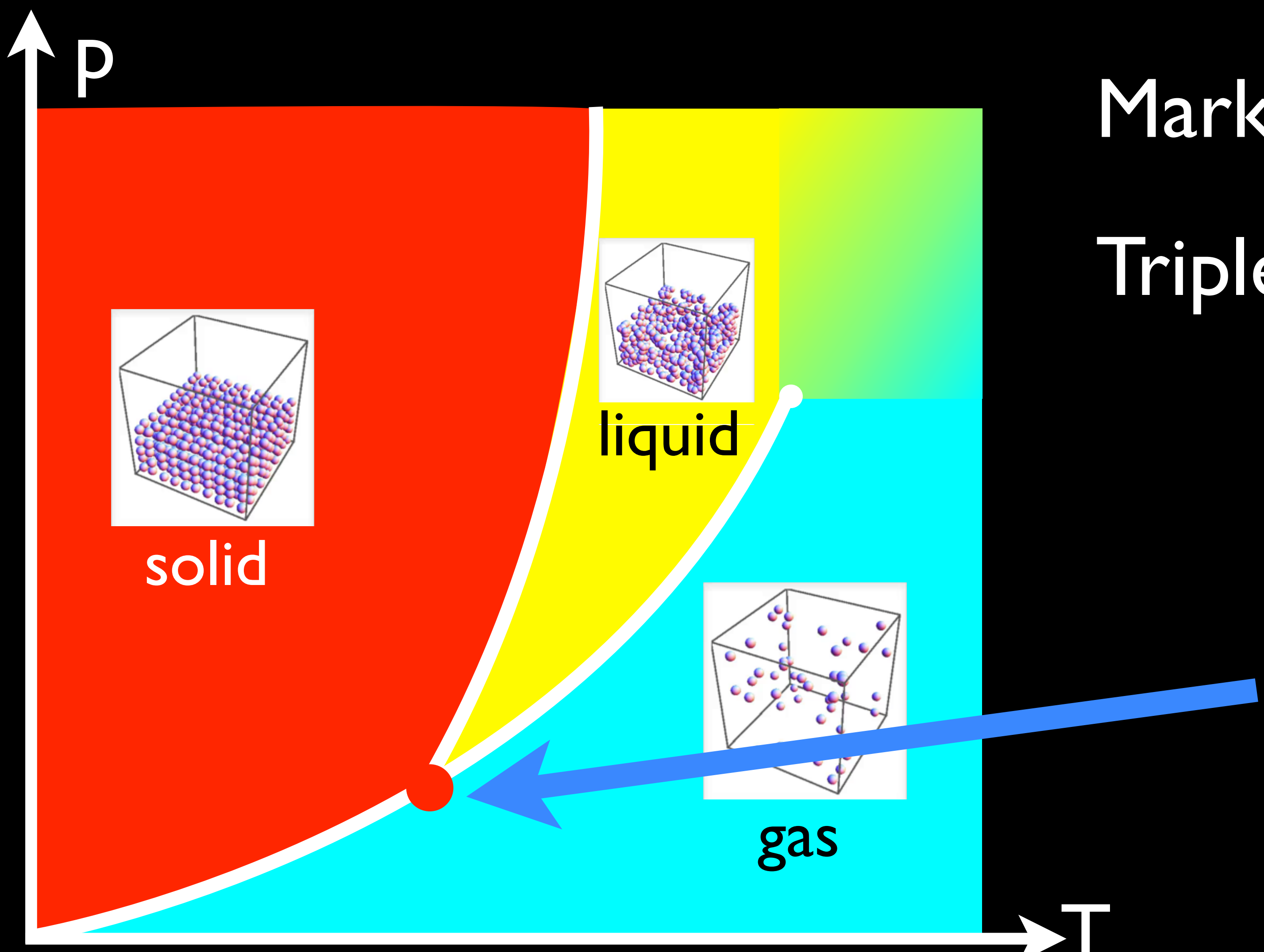
Phase diagram: plot of pressure vs. temperature

Mark phase transitions



Phase diagrams

Phase diagram: plot of pressure vs. temperature

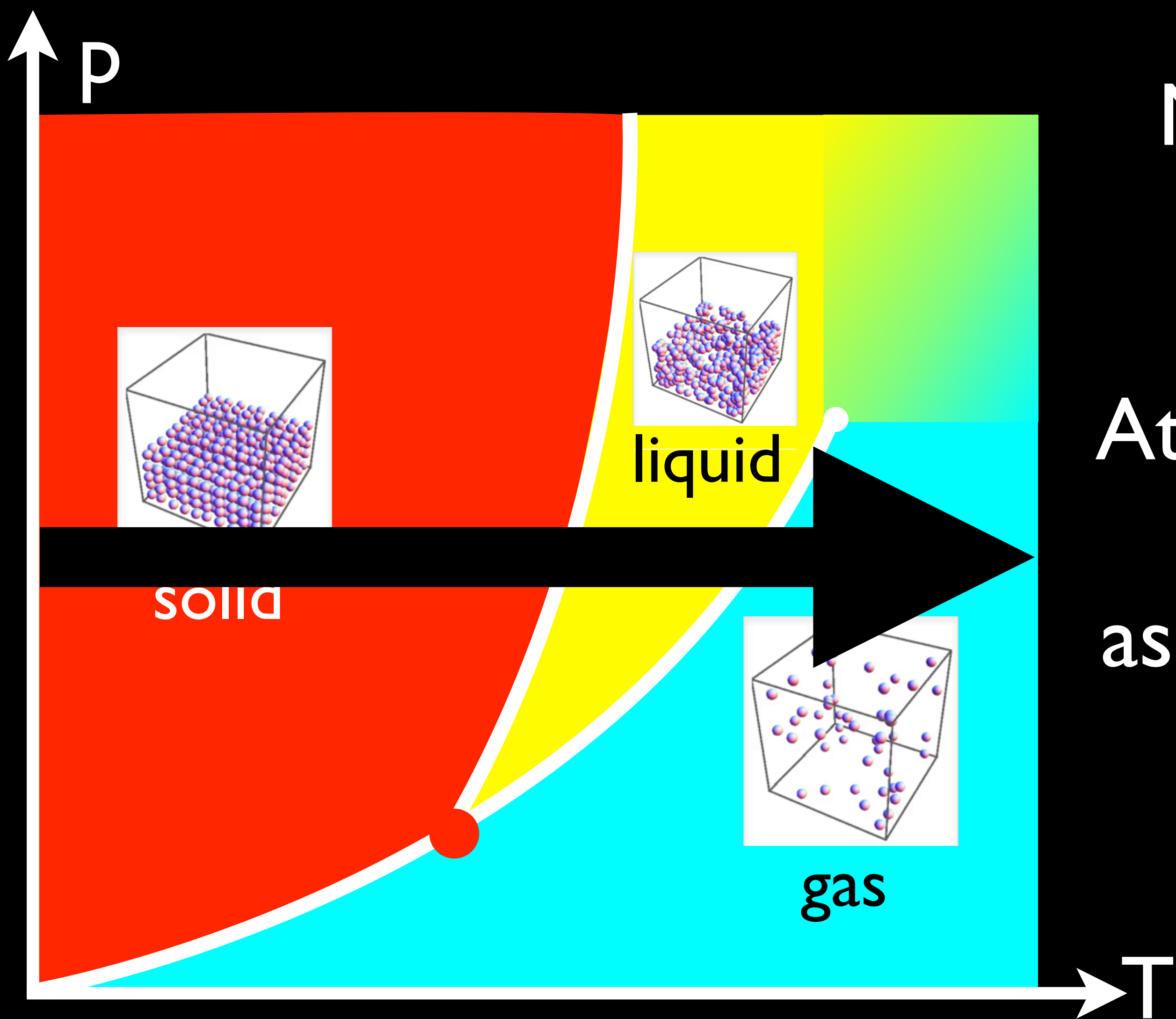


Mark phase transitions

Triple point: solid, liquid, gas all exist

Phase diagrams

Phase diagram: plot of pressure vs. temperature



Mark phase transitions

At atmospheric (normal) p,

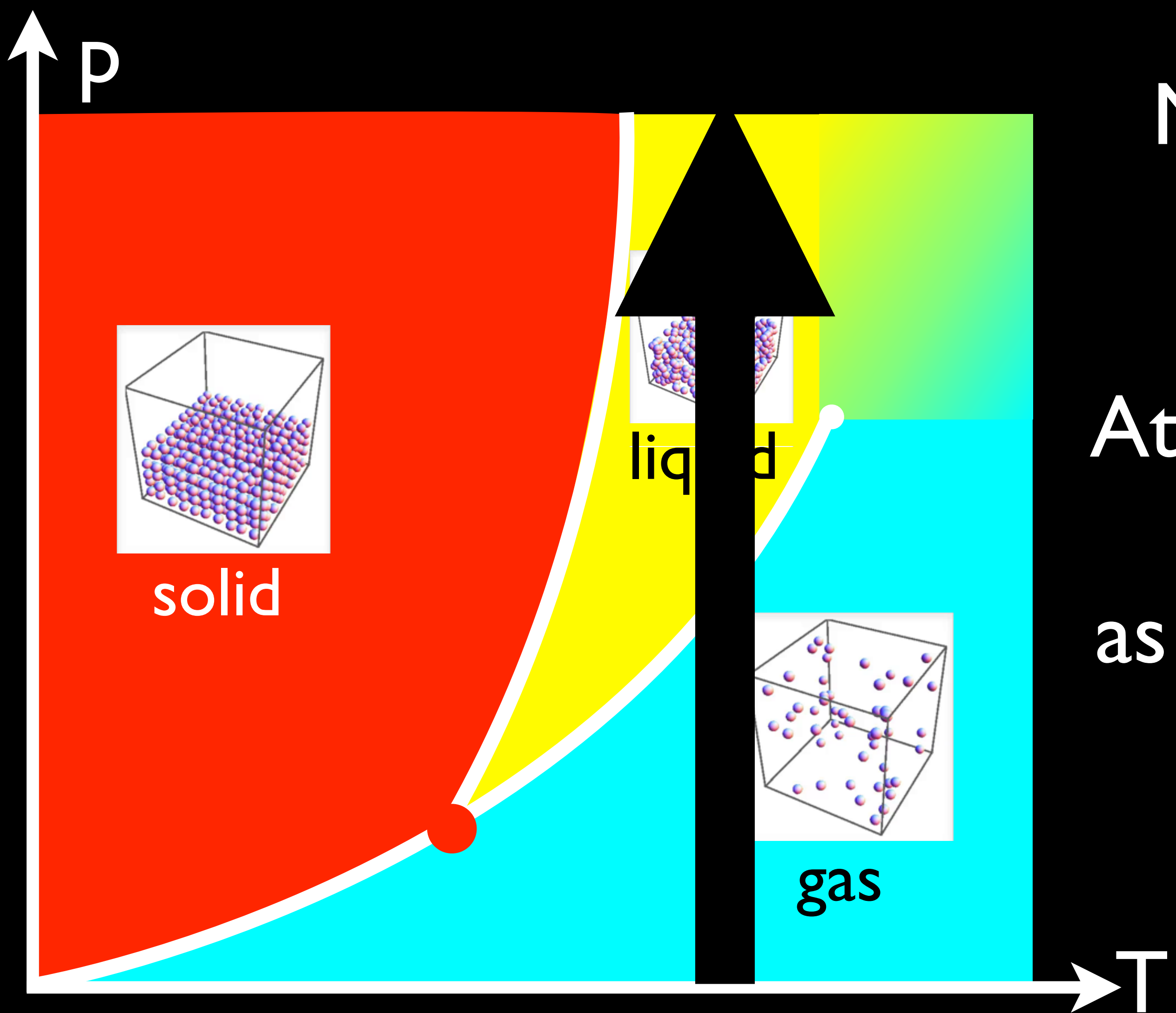
as T ↑: solid liquid gas phase change

Note: phase change is not fast!

Crossing lines takes a lot of energy

Phase diagrams

Phase diagram: plot of pressure vs. temperature



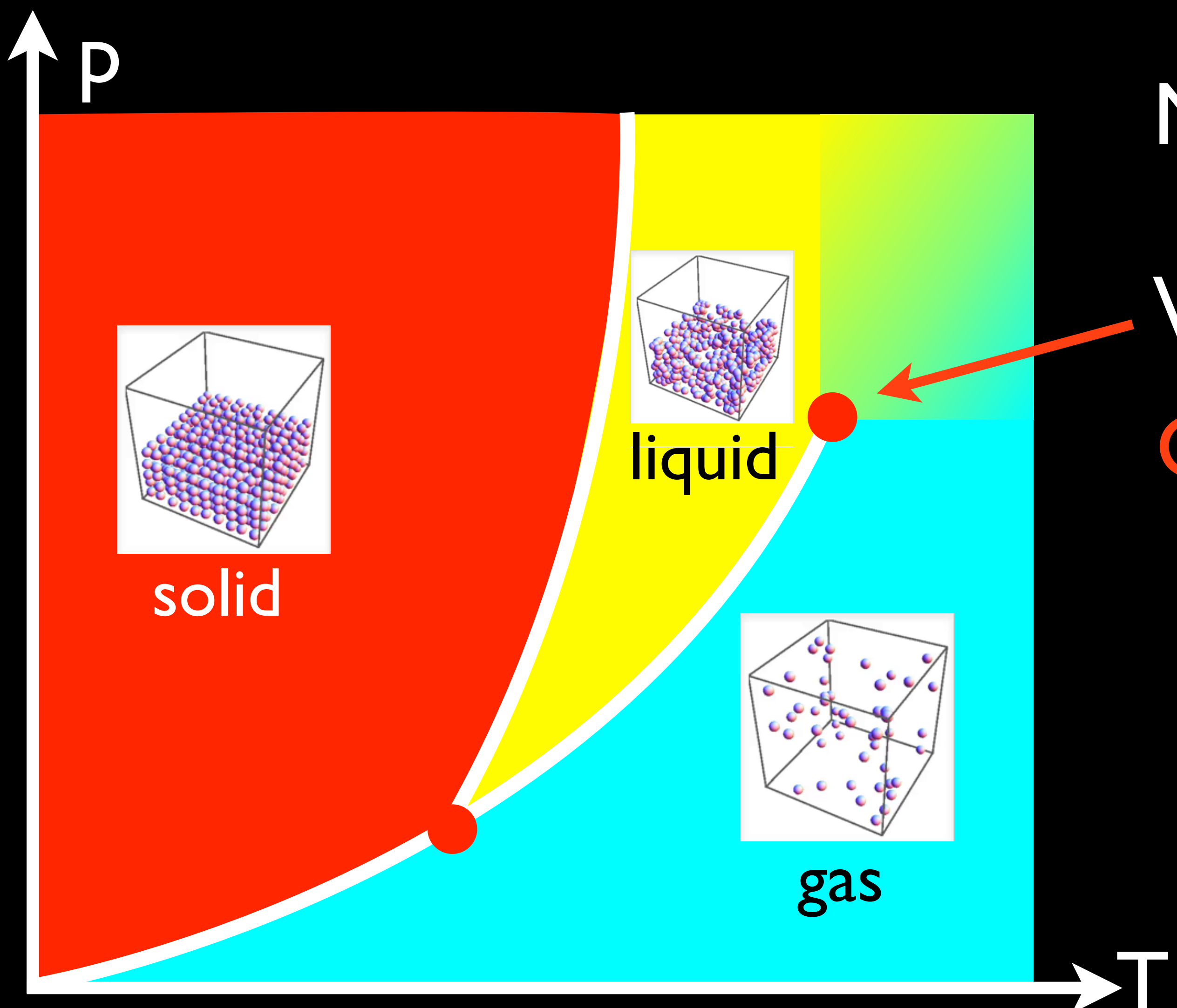
Mark phase transitions

At constant T

as p ↑: phase change without heat input

Phase diagrams

Phase diagram: plot of pressure vs. temperature



Mark phase transitions

What happens here?

Critical point :

Sudden phase change disappears

No clear boundary between liquid and gas

gas changes gradually into liquid

Phase diagrams Quiz

Everest Base Camp is at 5365 m.

Water will boil here at:

(a) $100^\circ\mathrm{C}$

(b) $> 100^\circ\mathrm{C}$

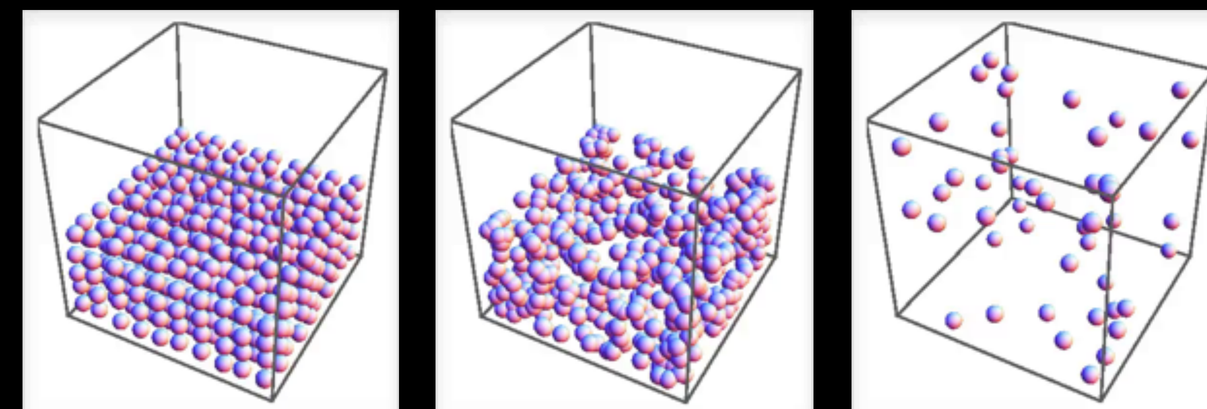
(c) $< 100^\circ\mathrm{C}$

(d) $< 0^\circ\mathrm{C}$

Thermal Expansion

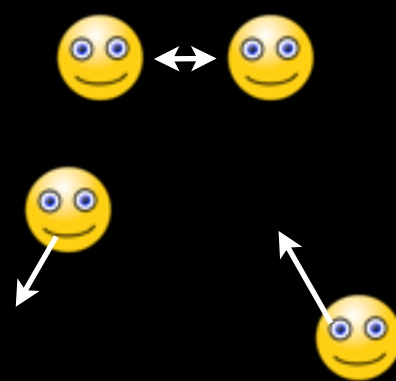
Gas: $pV = nRT \longrightarrow V \propto T$

Also true for liquid and solid but...



molecules closer

than in a gas.



harder to expand and compress

Define how much solid/liquid expands:

coefficient of volume expansion $$\beta = \frac{\Delta V/V}{\Delta T}$$

(assumes β not dependent on T and constant p)

Thermal Expansion

If object is long and thin...

Expansion / contraction greatest in 1D

$$\alpha = \frac{\Delta L / L}{\Delta T}$$

$$\beta = 3\alpha$$

↑

only important to solids

(liquids / gases can change shape)

Thermal Expansion — Quiz

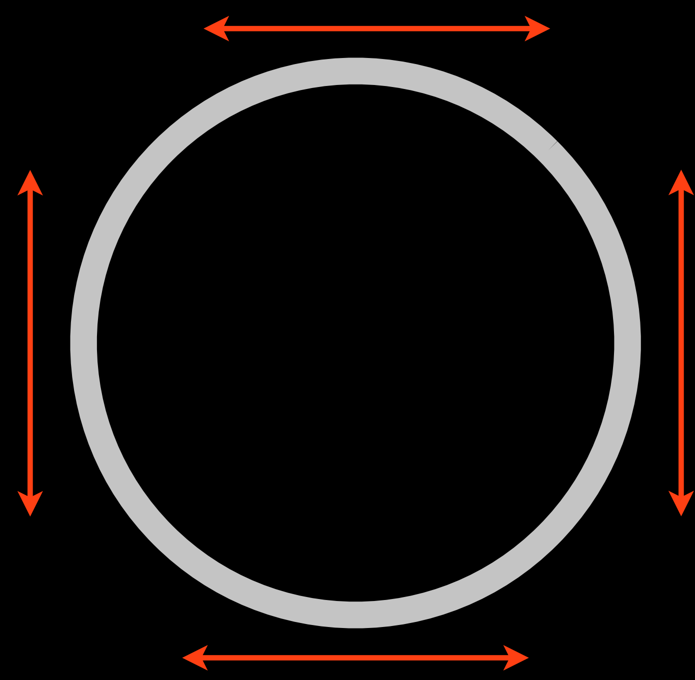
You heat up an iron ring.

The hole in the middle...

(a) larger?

(b) smaller?

(c) does not change?



all dimensions expand equally

Thermal Expansion

Table 17.2 Expansion Coefficients*

Solids	α (K^{-1})	Liquids and Gases	β (K^{-1})
Aluminum	24×10^{-6}	Air	3.7×10^{-3}
Brass	19×10^{-6}	Alcohol, ethyl	75×10^{-5}
Copper	17×10^{-6}	Gasoline	95×10^{-5}
Glass (Pyrex)	3.2×10^{-6}	Mercury	18×10^{-5}
Ice	51×10^{-6}	Water, 1°C	-4.8×10^{-5}
Invar†	0.9×10^{-6}	Water, 20°C	20×10^{-5}
Steel	12×10^{-6}	Water, 50°C	50×10^{-5}

*At approximately room temperature unless noted.

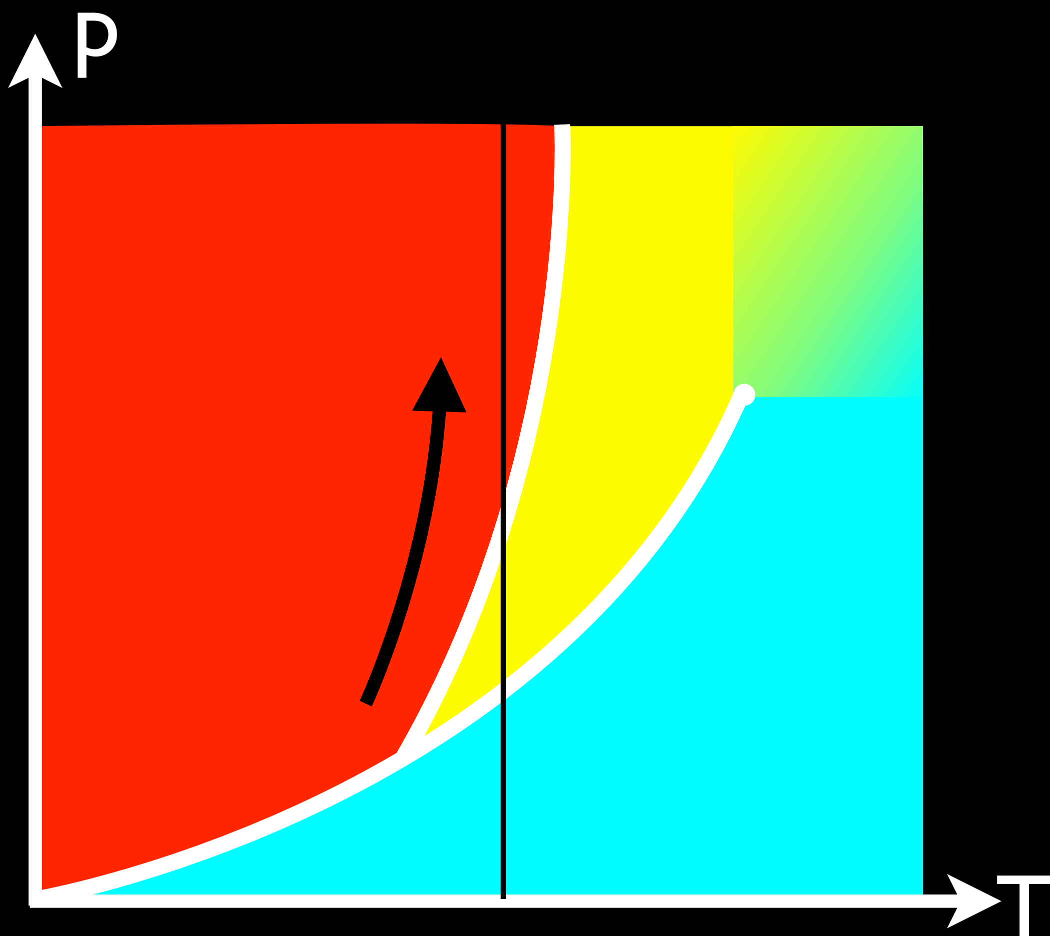
†Invar, consisting of 64% iron and 36% nickel, is an alloy designed to minimize thermal expansion.

64 % iron, 36% nickel: designed for small thermal expansion

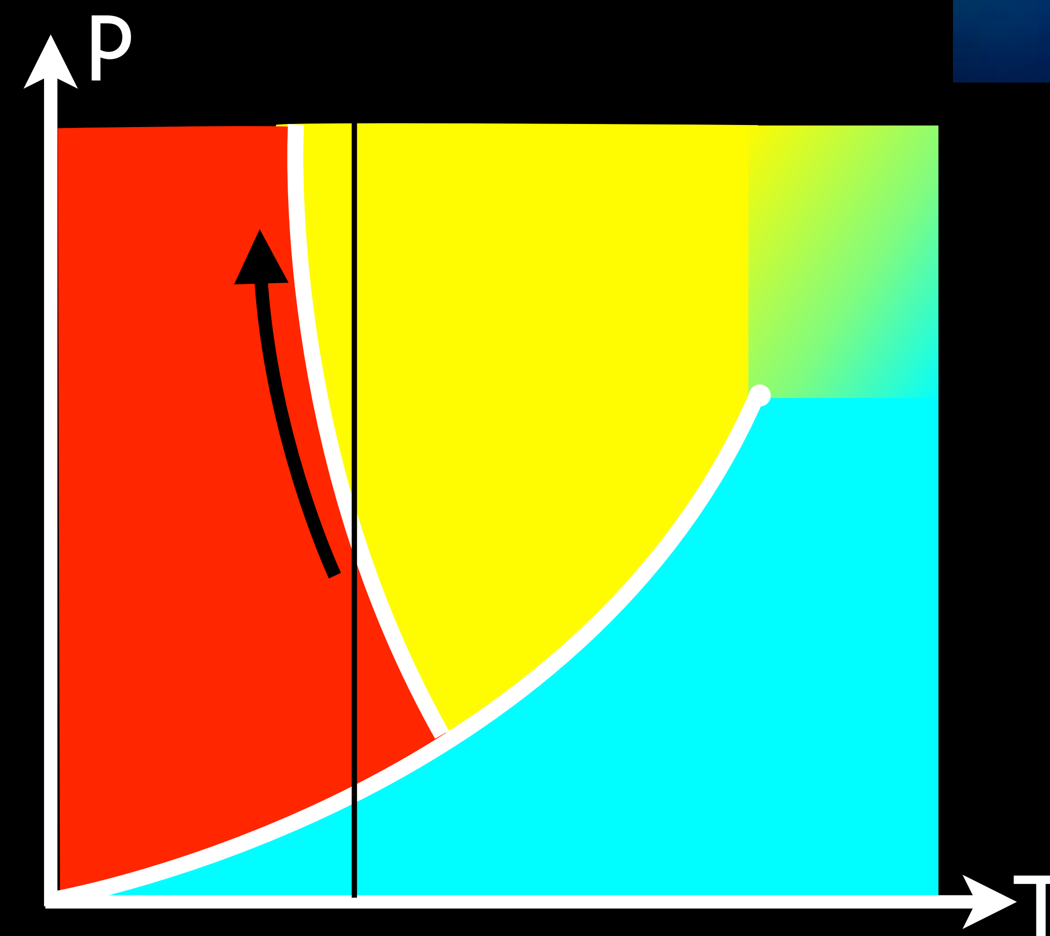
.... negative?

Thermal Expansion

Water .... is strange



normal



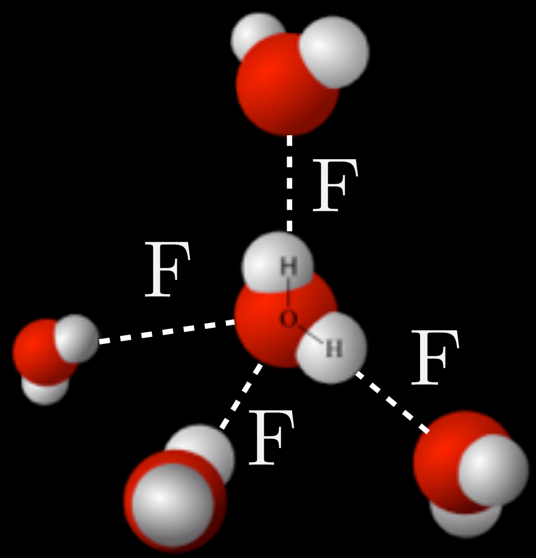
water

At constant T ...

Solid will melt if P *decrease*

Solid will melt if P *increased*

Thermal Expansion



Water is H_2O

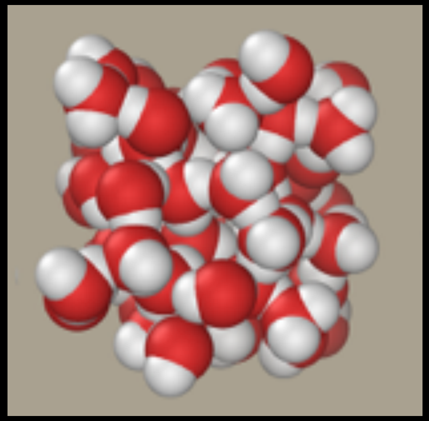
↓

2 hydrogen atoms ●

1 oxygen atom ●

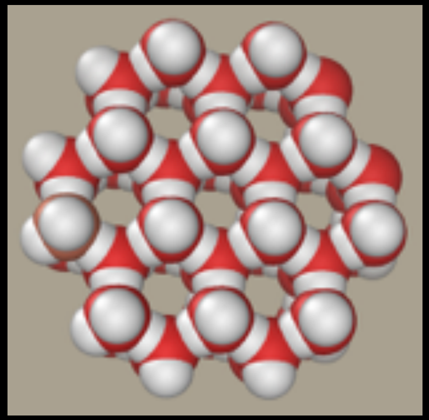
force between molecules (with H)

'*Hydrogen bonding*'



In water, *hydrogen bonding* moves molecules close

➡ dense structure



In ice, fixed structure moves molecules apart

➡ less dense

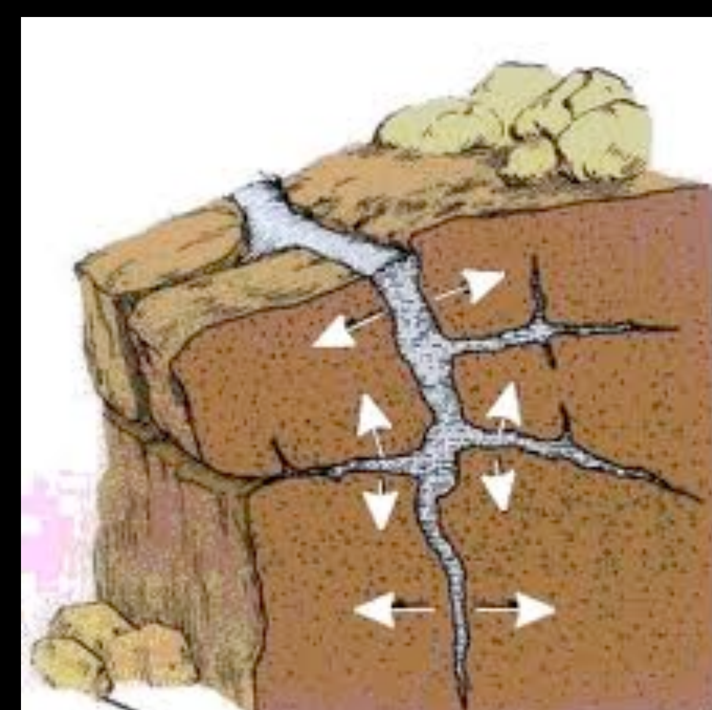
$> 4°C$ high K moves molecules apart again.

➡ densest water at $4°C$

Thermal Expansion

Good for sea life!

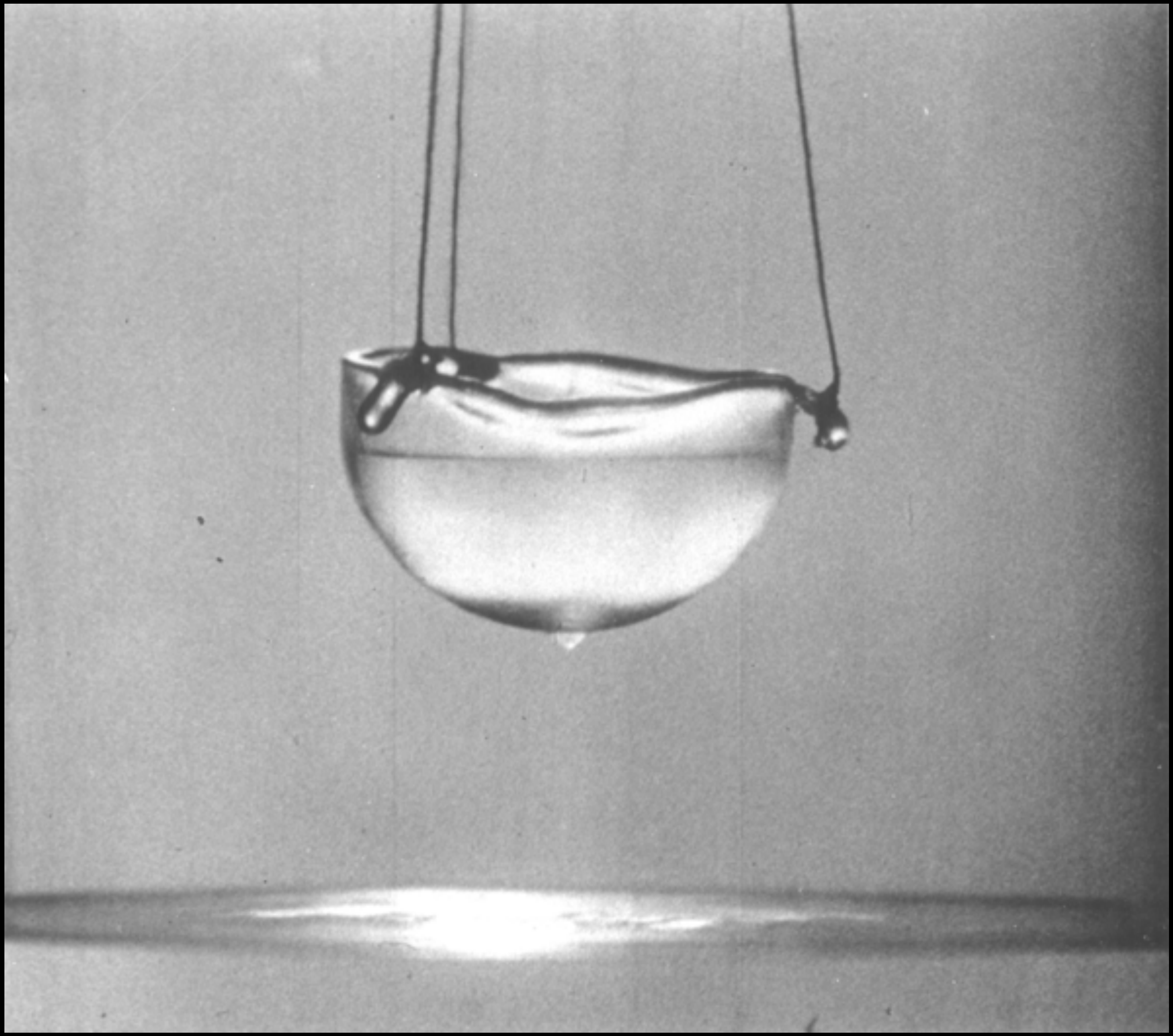
In winter, ice forms only on surface



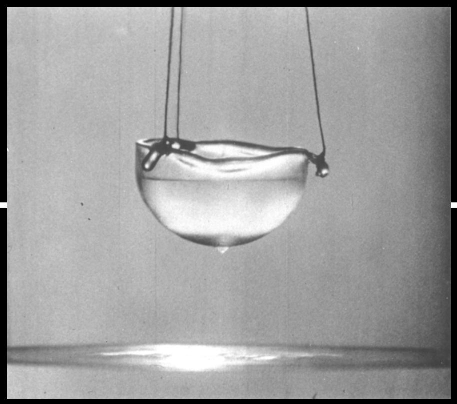
Bad for roads!

Physics in action

Superfluids



Superfluids

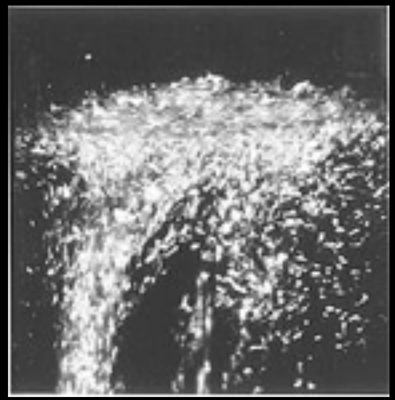


Helium-4 ($^4\mathrm{He}$) facts:

Liquid-gas change:
(Boiling point)

$-269°\mathrm{C}$

$4\,\mathrm{K}$



Very difficult to make helium-4 a liquid by cooling!

(Helium-4 is only a solid at very high pressures)

Below 2.17 K, helium-4 goes through a new phase change to become a superfluid

Superfluids

When do molecules (in theory) stop moving?

(a) $101^\circ\mathrm{C}$

(b) $0^\circ\mathrm{C}$

(c) 0 K

(d) They can never stop moving

Superfluids

How close to 0 K have scientists ever reached?

(a) $1 \times 10^{-9}\,\mathrm{K}$

(b) $1 \times 10^{-6}\,\mathrm{C}$

(c) 0 K

(d) $1 \times 10^{-6}\,\mathrm{K}$

Superfluids

What happens when the helium becomes a superfluid?

(a) the liquid bubbles

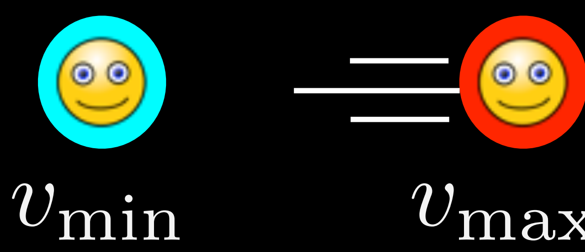
(b) the liquid becomes a gas

(c) the liquid becomes very still

(d) the liquid sublimes

Superfluids

The range of velocities in a superfluid are...



(a) much larger than normal fluid

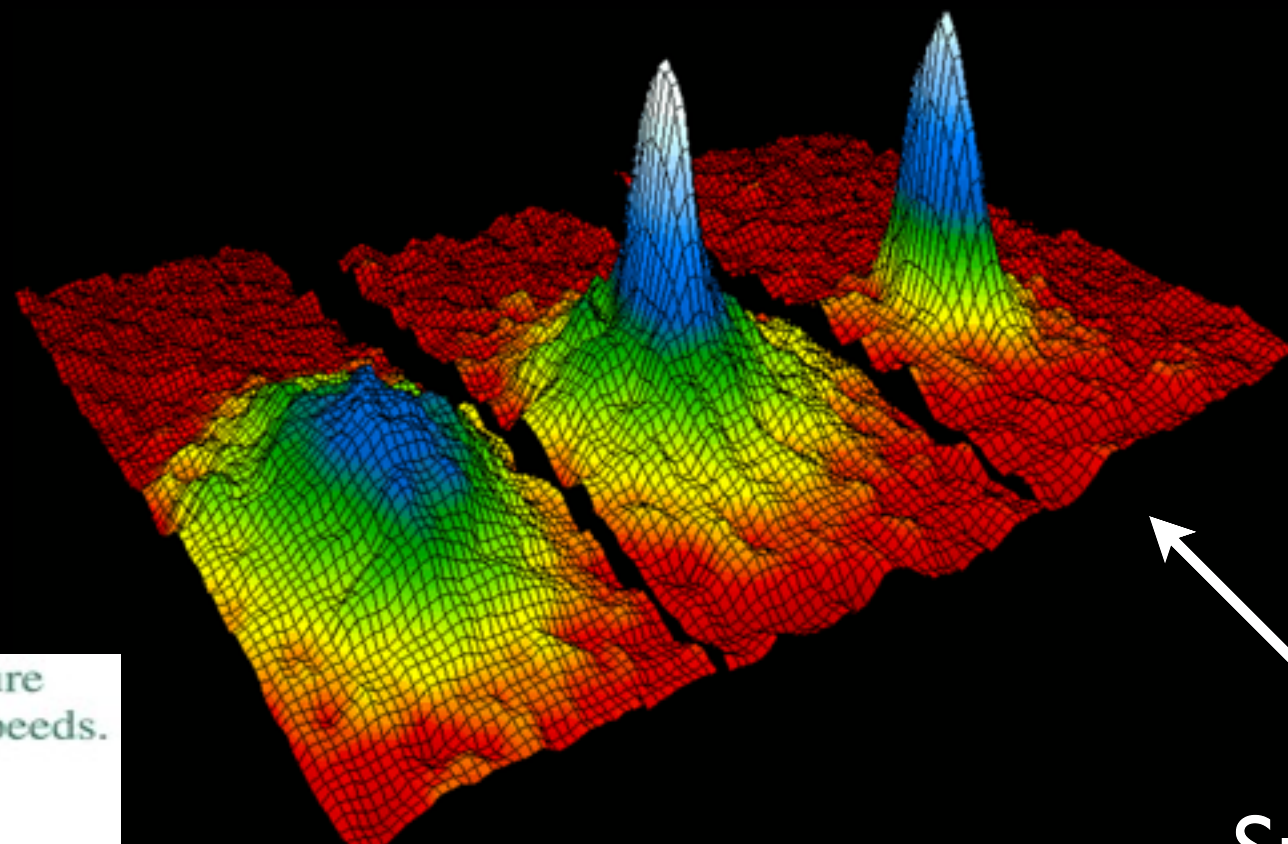
(b) same as normal fluid

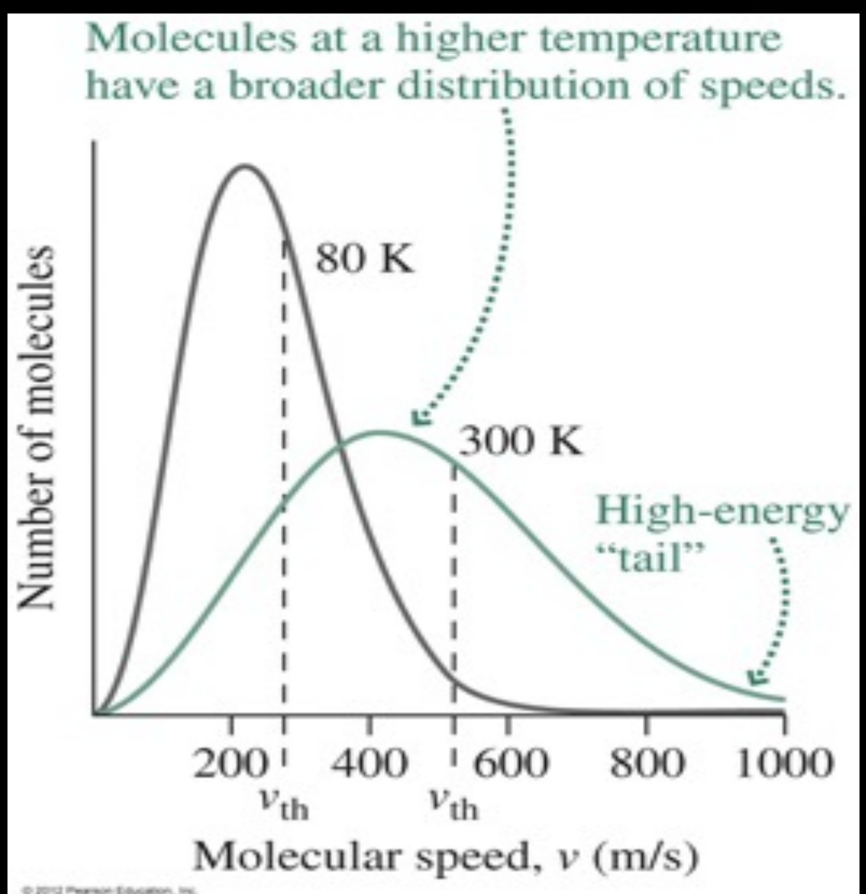
(c) much smaller than normal fluid

(d) (almost) infinity

Superfluids

Velocity distribution:





normal

Superfluid

Same T everywhere in fluid

VERY small velocity range

Maxwell-Boltzmann distribution

Superfluids

Why does the superfluid leak out of the bucket?

(a) the cold cracked the plug in the bucket

(b) Quantum mechanics changes the fluid properties

(c) it becomes a gas and can escape the plug

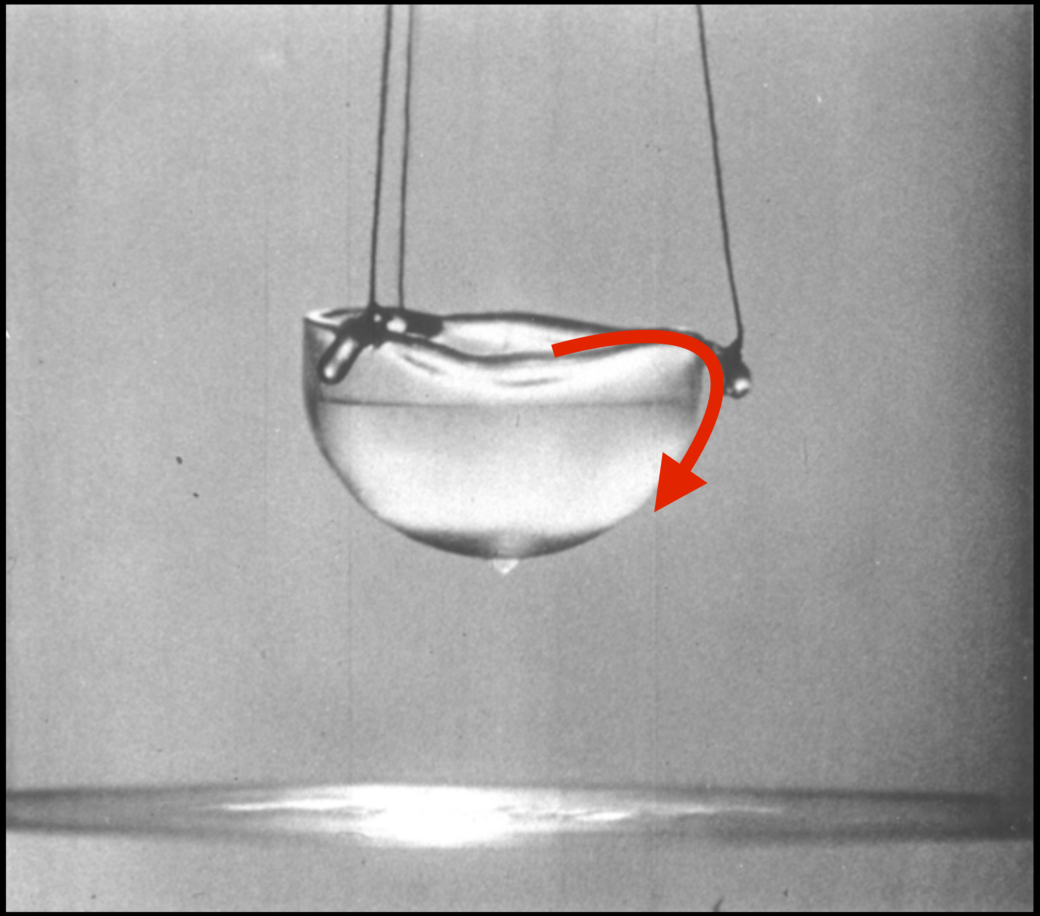
(d) no one knows

Superfluids

A superfluid has no viscosity

friction for fluids

Can move through tiny holes in containers



Also, spread out and and climb up walls