

PHY 117 HS2026

Week 6, Lecture 1

Oct. 20th, 2026

Prof. Ben Kilminster

Prof. Florencia Canelli

TODAY:

thermodynamics

OLAT Quiz stats: 677 students

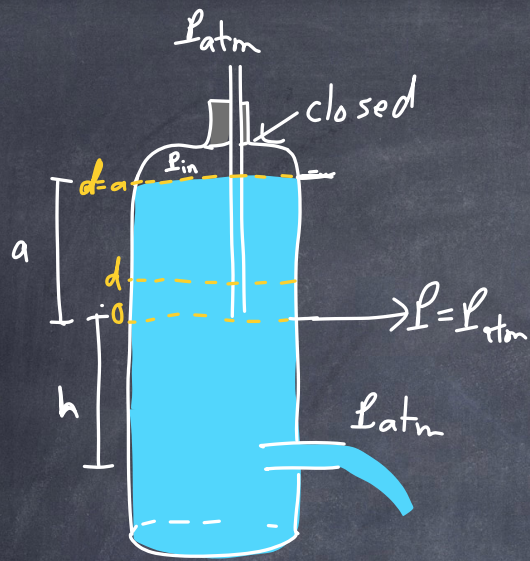
Quiz 1: 283

Quiz 2: 246

Quiz 3: 158

Quiz 4: 114

Quiz 5 + 6 come out this week.



Marriotte's bottle: constant velocity
water out of the hole.

The P_{atm} is transmitted to the depth marked as 0. (down to depth, "a").
 P_{in} must be $P_{atm} - \rho g d$.

The velocity will be $v = \sqrt{2gh}$

The benefit here is that the velocity of water remains constant while the height changes from $d=a$ to $d=0$

How does this work? P_{in} , pressure at top, will change.
The P_{in} will start out negative at the start, because this is a difference to P_{atm}

As d changes from $d=a$ to $d=0$ $\left\{ \begin{array}{l} P_{in} + \rho g d = P_{atm} \\ \uparrow \quad \quad \uparrow \\ \text{at top (increases)} \quad \text{as water falls, this decreases} \quad \text{bottom, constant} \end{array} \right.$

$P_{in} = P_{atm} - \rho g d$ $\left\{ \begin{array}{l} \text{when } d=a, P_{in} = P_{atm} - \rho g a \\ \text{when } d=0, P_{in} = P_{atm} \end{array} \right.$

for $d=a=10\text{cm}$, then

$$\rho g d = \left(\frac{1g}{cm^3}\right) \left(\frac{1kg}{1000g}\right) \left(\frac{100cm}{1m}\right)^3 \left(\frac{10m}{5s}\right) (10cm) \left(\frac{1m}{100cm}\right) = 1 \text{ kPa}$$

so we expect P_{in} to vary by 1 kPa as the water falls



From Marriotte's bottle (fluids)
to Marriotte's law (gas)



Boyle - Marriotte Law :
 $PV = \text{constant}$

with this, we start our unit on:

Thermodynamics - study of temperature, heat, and the exchange of energy.
(mechanical work)

Macroscopic scale: measurable properties:
volume, pressure, temperature.
 $\downarrow$
force/area

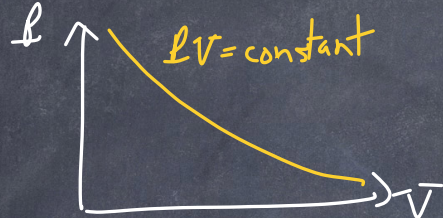
we will have 5 "k" variables
so I will write them differently:

K = Kelvin
 k = Boltzmann constant
 K = Kinetic energy

$k = \text{spring constant}$
 $\alpha = \text{coefficient of thermal conductivity}$

Ideal gases: randomly moving point particles with no inter-particle interactions.

Boyle - Marriotte Law: $PV = \text{constant}$ for an ideal gas at constant temperature



As we change temperature, the product of P and V takes different values:
The law is written as:

$$PV = nRT = NkT \quad \text{Ideal gas law}$$

pressure $[P_a] = \left[\frac{N}{m^2} \right]$

volume $[m^3]$

temperature $[K]$

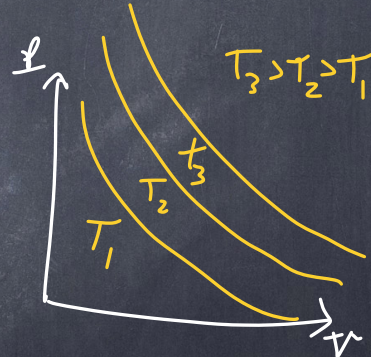
N : number of gas molecules
 k : Boltzmann constant, $k = 1.38 \times 10^{-23} \text{ J/K}$

n : number of moles
 R : gas constant, $R = 8.314 \text{ J/K.mol}$

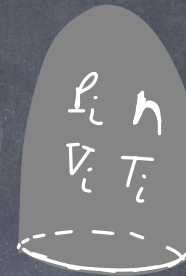
we see that $nR = Nk$

Note: $R = N_A \cdot k$
 $N = n \cdot N_A$

where N_A : Avogadro's number
molecules/mole
 $N_A = 6.02 \times 10^{23} \text{ molecules/mole}$



Why does our hot air balloon rise when air inside is heated?
 pressure decreases?
 density decreases?
 volume increases?



Visually:

before heating

during heating

after heating



P_i : pressure inside

$P_i = P_{atm}$

V_i = volume inside

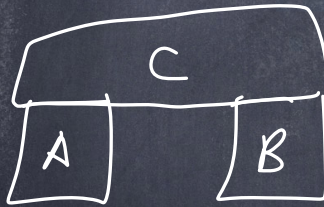
n_i = # moles air inside

T_i = temp. inside



what is temperature? Temperature is a measure of the thermal state of a system that determines the direction in which heat flows. Objects have thermometric properties: gases, and most solids and liquids expand with temp. (if allowed to). Electrical resistance changes.

0th law of thermodynamics: If 2 objects are in thermal equilibrium with a third object, then they are in thermal equilibrium with each other (no net flow of heat).



place
A + B
in contact



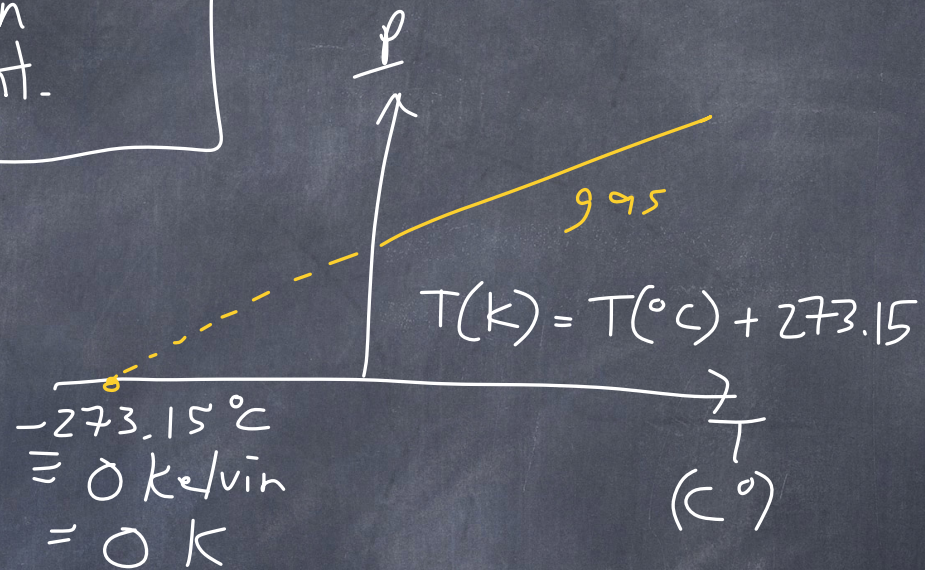
A + B
must be
the
same
temperature
(no thermometric
changes)

C: is in thermal
equilibrium with A + B
(no further thermometric
changes as no net heat flow)
C is the same temperature
as A + B

$$PV = nRT$$

$P \sim T$ in $[K]$
if V and n
stay constant.

Definition of $T = 0 K$



Since 2019, the Kelvin is defined
using $k = 1.380649 \times 10^{-23} \frac{J}{K}$ (exactly)

Since
the unit
Joule is

$$1 J = 1 \frac{kg \cdot m^2}{s^2}$$

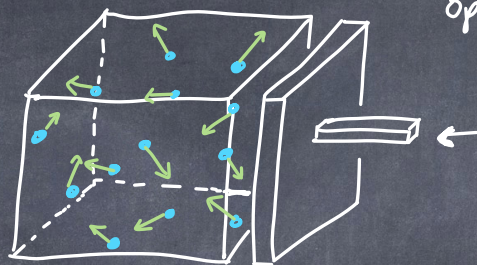
$$[K] = \frac{[kg \cdot m^2 \cdot s^{-2}]}{[k_B]}$$

Definition
of
1 Kelvin

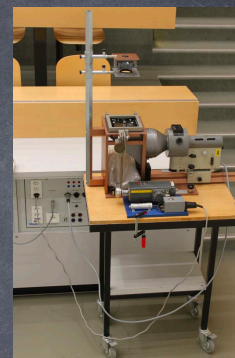
But what is temperature really?
At the molecular level?

box (5 closed sides)

piston pushing 6th open side

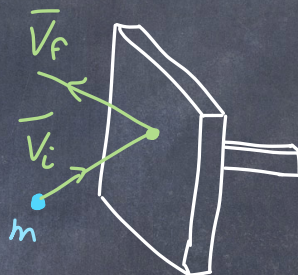


gas of molecules



we put molecules in the box, and close piston.

when one molecule hits the piston, its momentum changes.



initial: $\vec{v}_i = v_{ix}\hat{x} + v_{iy}\hat{y} + v_{iz}\hat{z}$
final: $\vec{v}_f = v_{fx}\hat{x} + v_{fy}\hat{y} + v_{fz}\hat{z}$

consider the x-direction: $\Delta p_x = m v_{fx} - m v_{ix}$

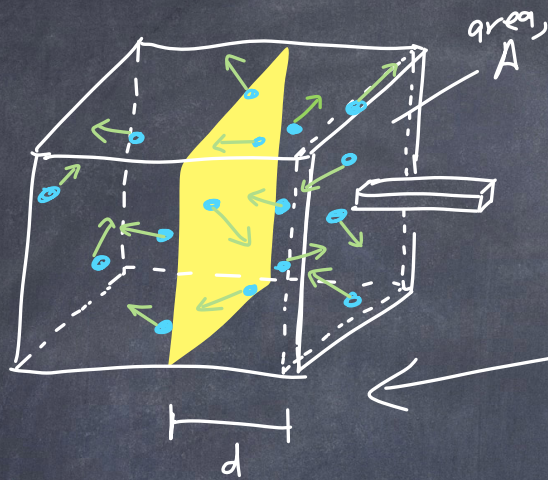
Assume it is an elastic collision, $|\vec{v}_f| = |\vec{v}_i|$

$$|v_{fx}| = |v_{ix}|$$

$$\Delta p_x = 2m v_x \quad \text{for one molecule in the gas}$$

$$(\Delta \vec{p} = \text{Impulse} = \vec{I})$$

The total volume of box is V



In some time, Δt , molecules hit the piston. The ones that hit the piston must be less than a certain distance away from the piston, moving to the right, depends on velocity

$$V_x = \frac{d}{\Delta t} \Rightarrow d = V_x \Delta t$$

The volume of this smaller box is $A \cdot d = A \cdot V_x \Delta t$

The number of particles in the box that hit the piston in time, Δt :

$$\underbrace{N_R}_{\substack{\text{\# of molecules} \\ \text{that hit} \\ \text{the piston on right} \\ \text{in time } \Delta t}} = \underbrace{\frac{N}{V}}_{\substack{\text{density} = \\ \text{\#} / \text{volume}}} \cdot \underbrace{V_x \Delta t A}_{\substack{\text{volume} \\ \text{of molecules} \\ \text{with correct} \\ V_x \text{ to hit} \\ \text{wall}}} \cdot \underbrace{\frac{1}{2}}_{\substack{\text{moving} \\ \text{to the} \\ \text{right}}}$$

The total momentum change of all ptcls hitting piston:

$$\underbrace{\Delta p_x}_{\text{momentum change of all molecules}} = \underbrace{\left(\frac{1}{2} \frac{N}{V} v_x \Delta t A \right)}_{\# \text{ molecules}} \underbrace{\left(2 m v_x \right)}_{\Delta p_x \text{ for one molecule}}$$

$$\Delta p_x = \frac{N}{V} m v_x^2 A \Delta t$$

The total force on the wall is $F_x = \frac{dp_x}{dt} = \frac{\Delta p_x}{\Delta t}$

$$F_x = \frac{N}{V} m v_x^2 A \frac{\cancel{\Delta t}}{\cancel{\Delta t}}$$

Pressure is F/A

$$P = \frac{N}{V} m v_x^2 \frac{\cancel{A}}{\cancel{A}}$$

pressure due to
N molecules of
velocity v_x

so $PV = Nmv_x^2$
 rewrite as $PV = 2N \left(\frac{1}{2} mv_x^2 \right) = 2N \left(\begin{array}{l} \text{Kinetic} \\ \text{energy} \\ \text{of a} \\ \text{molecule} \\ \text{in 1-D} \end{array} \right)$
 we recognize that since $PV = NkT$,

then

$$\boxed{\begin{array}{l} \text{Kinetic} \\ \text{energy} \\ \text{of a single} \\ \text{molecule} \\ \text{in 1-D} \end{array} = \frac{1}{2} mv_x^2 = \frac{1}{2} kT}$$

$\frac{1}{2} kT$ is the average kinetic energy of one molecule moving in 1 dimension: $K_{1D} = \left\langle \frac{1}{2} mv_x^2 \right\rangle = \frac{1}{2} kT$

K_{1D} : kinetic energy from 1-direction
 k : Boltzmann constant

or $T = \frac{K_{1D}}{\frac{1}{2} k}$ This is Temperature

Now we know that temperature is just the kinetic energy of a molecule scaled by a constant

Note: $\langle V_x \rangle = 0$ since $\frac{1}{2}$ move in $+\hat{x}$
 $\frac{1}{2}$ move in $-\hat{x}$

but $\langle V_x^2 \rangle > 0$

Also, the molecule has equal velocity in x, y, z directions.

$$\text{so } K_{3D} = \frac{1}{2} m \langle V_x^2 \rangle + \frac{1}{2} m \langle V_y^2 \rangle + \frac{1}{2} m \langle V_z^2 \rangle$$

$$= 3 \left(\frac{1}{2} kT \right)$$

↑
3 degrees
of freedom
(x, y, z)

Kinetic energy per degree of freedom

$$K_{3D} = 3 \left(\frac{1}{2} m \langle V_x^2 \rangle \right)$$

because $\langle V_x^2 \rangle = \langle V_y^2 \rangle = \langle V_z^2 \rangle$

$$\langle V^2 \rangle = 3 \langle V_x^2 \rangle$$

we call $\sqrt{\langle V^2 \rangle} \equiv V_{rms}$ = "root mean square" speed.

For N particles, the translational kinetic energy (in 3 dimensions) is:

$$K_{sp} = N \left(\frac{3}{2} kT \right) = \frac{3N}{2} m \langle v_x^2 \rangle = \frac{N}{2} m \langle v^2 \rangle$$

$$\cancel{N} \left(\frac{3}{2} kT \right) = \frac{\cancel{N}}{2} m \langle v^2 \rangle \Rightarrow T = \frac{m \langle v^2 \rangle}{3k}$$

$$\langle v^2 \rangle = \frac{3kT}{m}$$

for 3 degrees of freedom

(independent of N)

Q: What is the rms speed of Neon molecules at room temperature?

$$T = 293 \text{ K}, \quad \text{molar mass of Neon} = M = 20.18 \text{ g/mol}$$

Velocity of particles in a gas:

$$\frac{1}{2} m \langle v^2 \rangle = \frac{3}{2} kT$$

$$v_{rms} = \sqrt{\langle v^2 \rangle} = \sqrt{\frac{3kT}{m}}$$

The distribution of velocities is (no derivation)

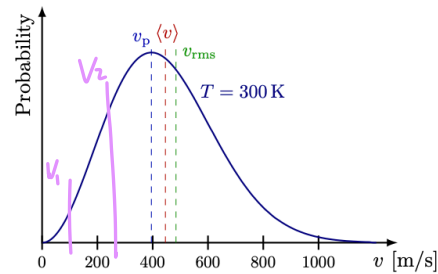
$$f(v) = \frac{4}{\sqrt{\pi}} \left(\frac{m}{2kT} \right)^{3/2} v^2 e^{-\frac{mv^2}{2kT}}$$

Maxwell-Boltzmann
distribution
for velocities

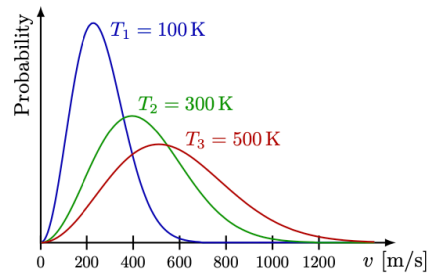
m : mass of 1 molecule
 v : velocity of a molecule
 T : temperature

If we had N molecules, we can find the number of molecules within a specific velocity range between v_1 and v_2 as:

$$N_{v_1 \rightarrow v_2} = \int_{v_1}^{v_2} N f(v) dv$$



(a) The distribution is asymmetric.



(b) For different temperatures.

Figure 17.4: Maxwell-Boltzmann distribution for oxygen gas O_2 with atomic weight ~ 16 per atom.

$$N_{v_1 \rightarrow v_2} = \int_{v_1}^{v_2} N f(v) dv$$

$v_p = v_{\max}$: speed for which $f(v)$ is maximum = $\sqrt{\frac{2kT}{m}}$

$\langle v \rangle$: mean of $f(v)$

$v_{rms} : \sqrt{\langle v^2 \rangle}$

we could rewrite $f(v)$ as $f(E)$

$$f(E) = \frac{2}{\sqrt{\pi}} \left(\frac{1}{kT} \right)^{3/2} E^{1/2} e^{-E/kT}$$

$E = K = \frac{1}{2} mv^2$
is kinetic energy

Maxwell-Boltzmann energy distribution

similarly

$$N_{E_1 \rightarrow E_2} = \int_{E_1}^{E_2} N f(E) dE$$

gives us a way of counting how many particles are in a kinetic energy range

Quiz 2:

The spring constant would be the same on the moon than on the earth. ($k = \frac{mg}{\Delta x}$, and g is different on the moon)

Unanswered

Right

Wrong

answer

3

125

117

k is a constant, independent of the type of force.
If we pull on a spring with any force F , it will extend by Δx , so $k = \frac{F}{\Delta x}$.

More info...

for instance, assume
 $g_{\text{moon}} = g_{\text{earth}}/6$



$$g_{\text{earth}} = 9.81 \text{ m/s}^2$$

To calculate k ,
we hang a weight.

$$k = \frac{F}{\Delta x} = \frac{mg_{\text{earth}}}{\Delta x_{\text{earth}}}$$



$$g_{\text{moon}} = 1.62 \text{ m/s}^2$$

$$\Delta x_m = \Delta x_{\text{earth}}/6$$

$$\begin{aligned} k &= \frac{mg_{\text{moon}}}{\Delta x_{\text{moon}}} \\ &= \frac{mg_{\text{earth}}/6}{\Delta x_{\text{earth}}/6} \\ k &= \frac{mg_{\text{earth}}}{\Delta x_{\text{earth}}} \end{aligned}$$

Quiz 3:

Question

What is true about a falling object?

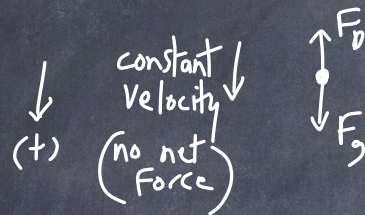
If the object reaches a constant velocity (terminal velocity), there is no net work on the object.

5



T

F



$$\Sigma F = F_g - F_D = 0$$

forces balance

F_g does (+) work

F_D does (-) work

$$W_g = +F_g \cdot \Delta x \quad W_D = -F_D \cdot \Delta x$$

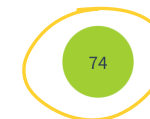
$$W_{net} = W_g + W_D = 0$$

T

F

The area under the velocity vs. time curve represents acceleration.

4



$$a = \frac{dv}{dt} = \frac{\Delta v}{\Delta t}$$

acceleration is the slope
of velocity vs. time

$$v = \frac{dx}{dt} \Rightarrow dx = v dt$$

$$\int dx = \int v dt$$

$$x = \int v dt$$

the area under v vs. t curve
is position

Quiz 4:

T

F

Unanswered

Right

Wrong

When torque is zero, angular momentum is zero.

2

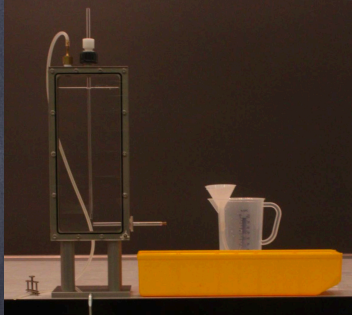
54

58

Imagine a wheel spinning at constant angular speed.

⇒ It has no torque so its not accelerating.

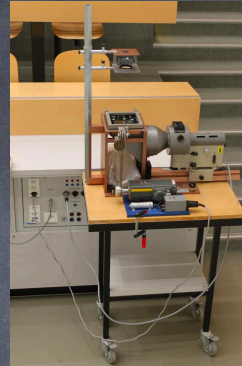
⇒ But it does have constant angular momentum
 $L = I\omega$.



H21



Th57



Th36



Th58



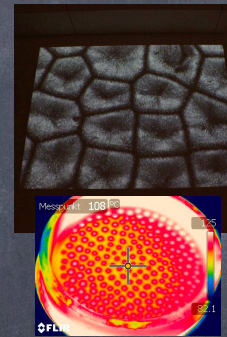
Th12



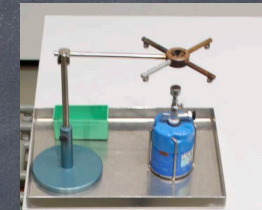
Th63



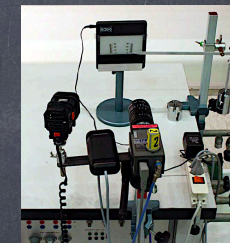
Th54



Th35



Th20



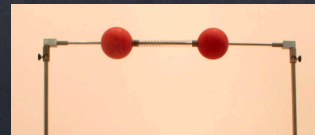
E12



Th19



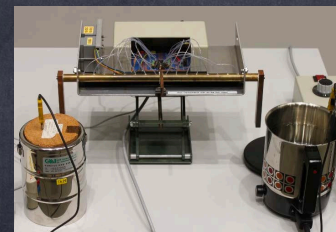
Th28



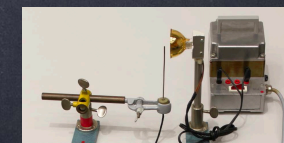
Th27



Th2



Th22



Th48