Personal Information 1

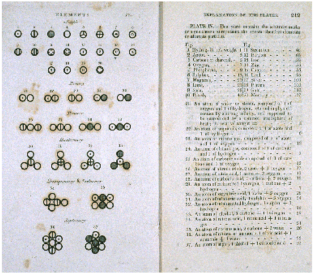
- Name:
- Did you take Phys 131 and who was your instructor?
- How many semesters of physics before this course (high school or college)?
- How many semesters of calculus before this course (high school or college)?
- Preferred personal pronouns?

What are you made of and how do you know? 2

What are you made of and how do you know? 3

Dalton's Atomic Theory (1808)

1. All matter consists of tiny particles.
2. Atoms are indestructible and unchangeable.
3. Elements are characterized by the mass of their atoms.
4. When elements react, their atoms combine in simple, whole-number ratios.



from *A New System of Chemical Philosophy (1808)* by John Dalton

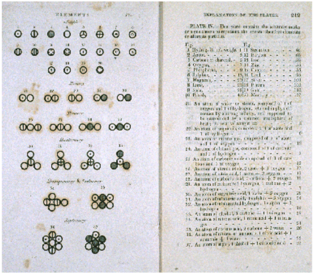
What are you made of and how do you know? 4

Dalton's Atomic Theory (1808)

1. All matter consists of tiny particles.
2. Atoms are indestructible and unchangeable.
3. Elements are characterized by the mass of their atoms.
4. When elements react, their atoms combine in simple, whole-number ratios.

Boltzmann's Kinetic Theory (1905)

1. Matter consists of tiny particles.
2. Use Newtonian physics to calculate ideal gas properties like the heat capacity/specific heat.
3. Connects bulk properties to microscopic motion of atoms.



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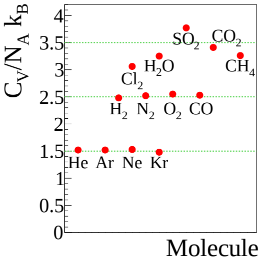


Specific Heats of Ideal Gases 5

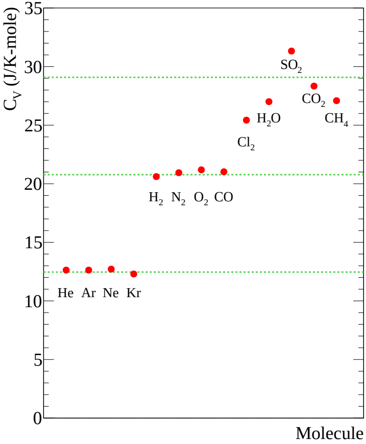
Assume that a pure, ideal gas is made of tiny particles that bounce into each other and the walls of their cubic container of side ℓ. Show the average pressure P exerted by this gas is

$$P = \frac{1}{3}\frac{N}{V}m\overline{v^2_{total}}$$

Use the ideal gas law ($PV = Nk_BT = nRT$)and the conservation of energy ($\Delta E_{int} = C_V \Delta T$) to calculate the specific heat of an ideal gas and show the following.

$$C_V = \frac{3}{2}N_A k_B$$

Is this right?



N - number of particles

k_B - Boltzmann constant

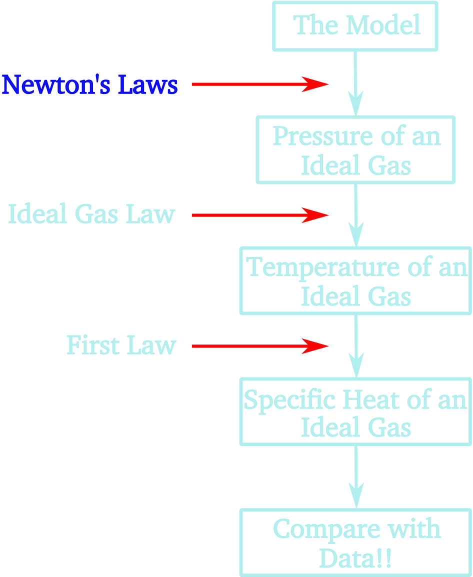
N_A - Avogadro's number

$V = \ell^3$

m - atomic mass

v_{total} - atom's speed

The Plan



The Model

Newton's Laws

Pressure of an Ideal Gas

Ideal Gas Law

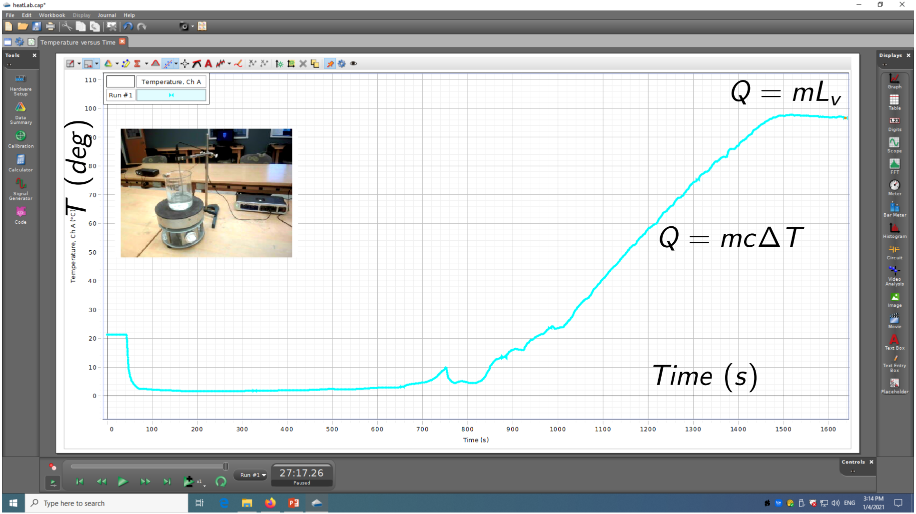
Temperature of an Ideal Gas

First Law

Specific Heat of an Ideal Gas

Compare with Data!!

Temperature and Heat 7



$$Q = mL_v$$

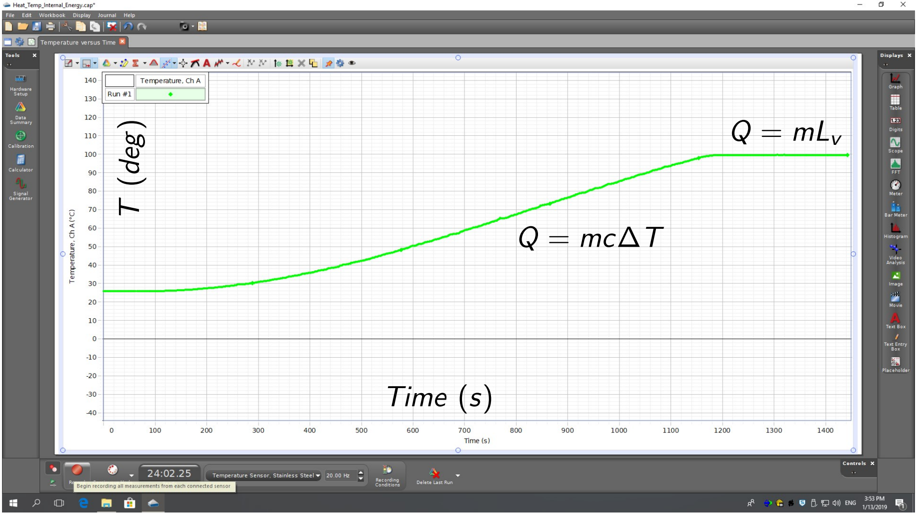
$$Q = mc\Delta T$$

T (deg)

$Time$ (s)

Temperature and Heat

8



Begin recording all measurements from each connected sensor

$Q = mL_v$

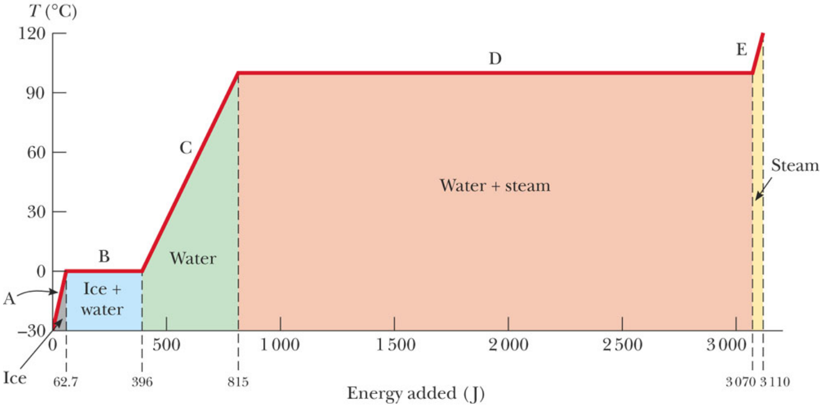
$Q = mc\Delta T$

T (deg)

Time (s)

Temperature and Heat

Heat (Q) is thermal energy transferred from one place or body to another due to a difference in temperature. Thermal energy is the mechanical energy (kinetic and potential) associated with atomic motion in an object.



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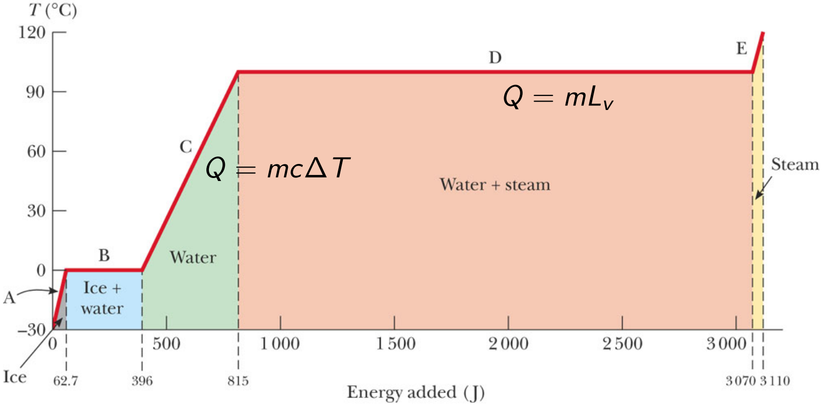

$Q = mL_v$

$Q = mc\Delta T$

Calorimetry/Energy Conservation 11

Two ice cubes each with mass $m_I = 0.050\ kg$ are taken from a freezer at $T_0 = 0^\circ\mathrm{C}$ and dropped into a container holding $m_w = 1.0\ kg$ of water at $T_1 = 25^\circ\mathrm{C}$. What will be the final temperature of the liquid? Assume the container absorbs no heat.

$c_{ice} = 2090\ J/kg - K$
$c_w = 4186\ J/kg - K$
$L_f = 3.33 \times 10^5\ J/kg$

Calorimetry/Energy Conservation

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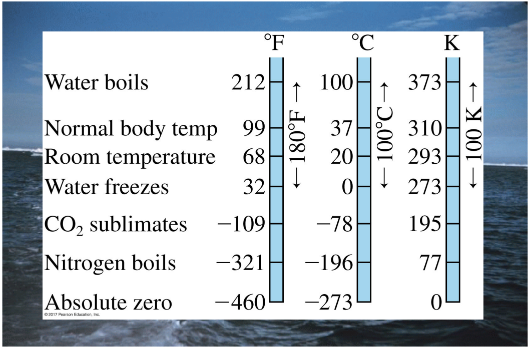
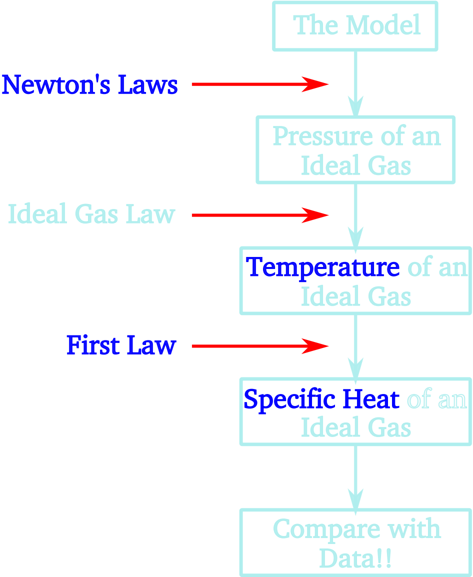


	°F	°C	K
Water boils	212	100	373
Normal body temp	99	37	310
Room temperature	68	20	293
Water freezes	32	0	273
CO_2 sublimates	−109	−78	195
Nitrogen boils	−321	−196	77
Absolute zero	−460	−273	0

$$c_{ice} = 2090\ J/kg - K$$
$$c_w = 4186\ J/kg - K$$
$$L_f = 3.33 \times 10^5\ J/kg$$

The Plan



The Model

Newton's Laws

Pressure of an Ideal Gas

Ideal Gas Law

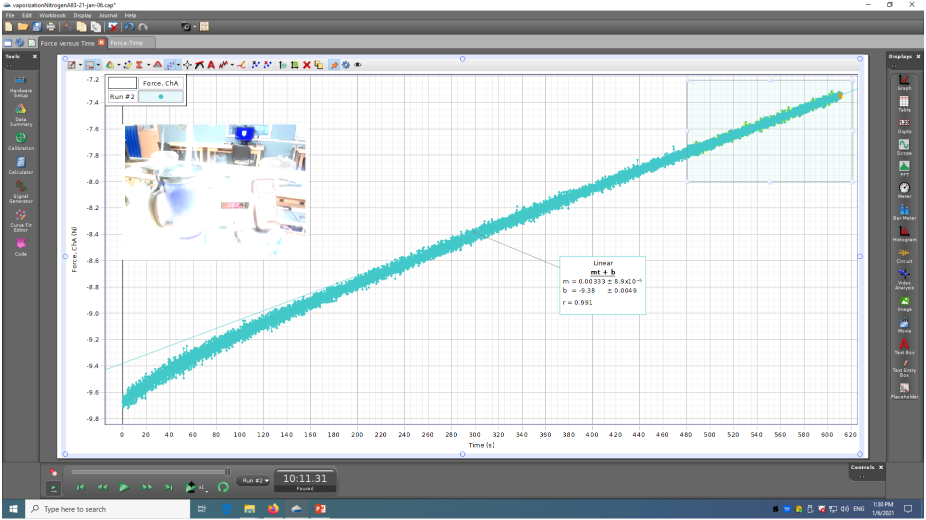
Temperature of an Ideal Gas

First Law

Specific Heat of an Ideal Gas

Compare with Data!!

Heat of Vaporization of Liquid Nitrogen Lab 14

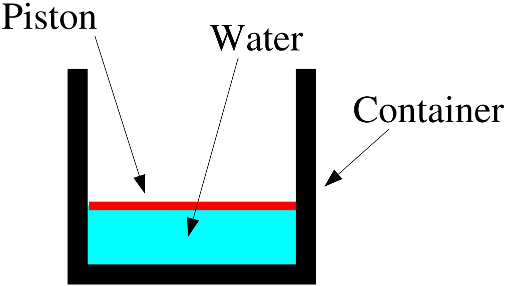


Linear
mt + b
m = 0.00333 ± 8.9×10^{-6}
b = -9.38 ± 0.0049
r = 0.991

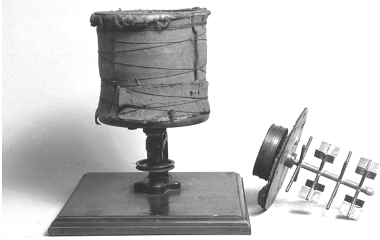
The First Law of Thermodynamics

Let 1.00 *kg* of liquid water at 100° C be converted to steam at 100° C. The water is contained in a cylinder with a movable piston of negligible mass that sits right on top of the water at the start. The volume changes from an initial value of $1.00 \times 10^{-3}\ m^3$ as a liquid to $1.671\ m^3$ as steam. The latent heat of vaporization of water is $L_V = 2.26 \times 10^6\ J/kg$ and atmospheric pressure is $P_{atm} = 1.01 \times 10^5\ Pa$.

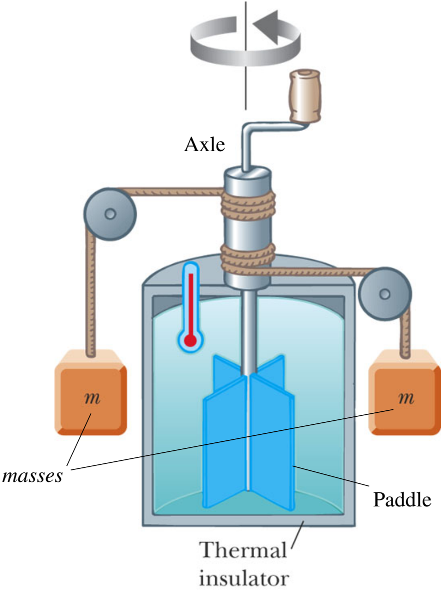
1. How much work is done by this process?
2. How much heat must be added?
3. What is the change in the water's internal energy?



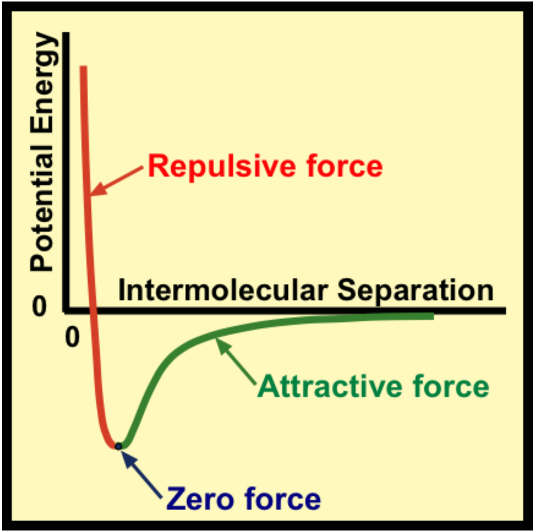
The Mechanical Equivalent of Heat 16



Joule's original apparatus



What Happens at the Phase Change? 17



The energy diagram for two atoms.

Ideal Gases

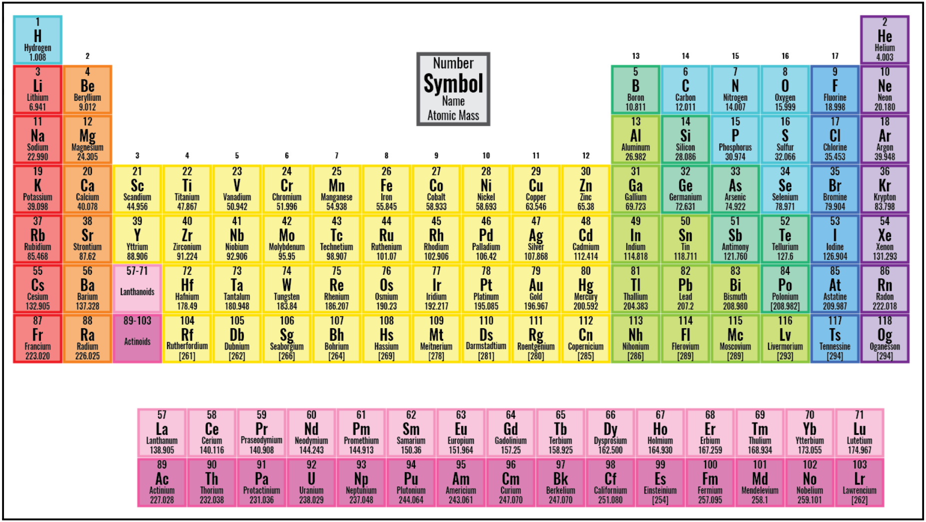
18

A weather balloon is loosely inflated to a volume $V_0 = 2.2\ m^3$ with helium at a pressure of $P_0 = 1.0 \times 10^5\ Pa$ and a temperature $T_0 = 20^\circ\mathrm{C}$. At an elevation of 20,000 ft the atmospheric pressure is down to $P_1 = 0.5 \times 10^5\ Pa$ and the temperature is $T_1 = -48^\circ\mathrm{C}$. The bag can expand freely. What is the new volume of the bag? What is the gas mass?

Ideal Gases

19

A weather balloon is loosely inflated to a volume $V_0 = 2.2\ m^3$ with helium at a pressure of $P_0 = 1.0 \times 10^5\ Pa$ and a temperature $T_0 = 20^\circ\mathrm{C}$. At an

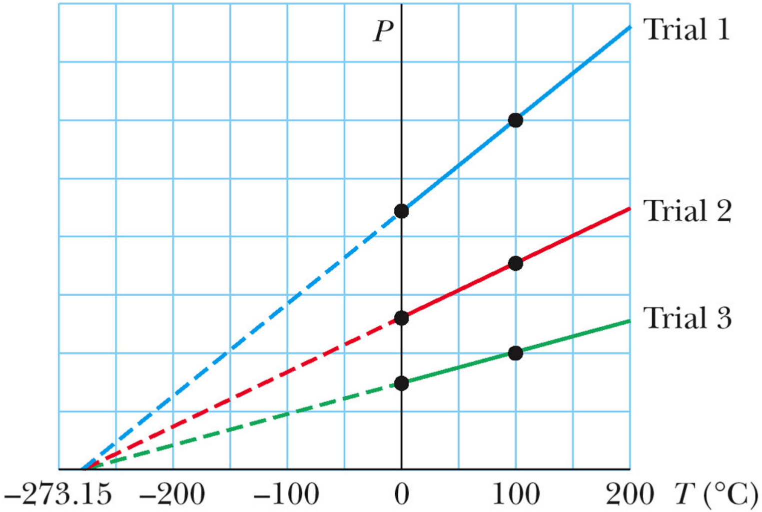


Number
Symbol
Name
Atomic Mass

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.293
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinoids	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]

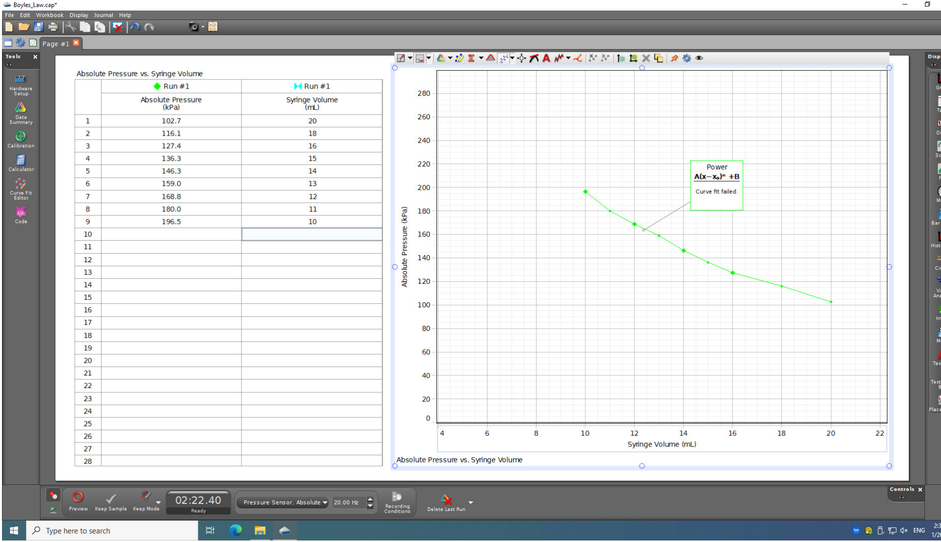
57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Absolute Zero and Ideal Gases



A steel tank contains $m_g = 0.30\ kg$ of ammonia gas $(\mathrm{NH_3})$ at an absolute pressure $P_0 = 1.35 \times 10^5\ N/m^2$ and a temperature $T_0 = 77^\circ\ C$. What is the volume of the tank? At a later time the tank is checked. The temperature has fallen to $T_1 = 22^\circ\ C$ and the pressure has fallen to $P_1 = 8.7 \times 10^5\ N/m^2$. How many kilograms of gas leaked out of the tank?

Boyle’s Law for Ideal Gases - 1



Absolute Pressure vs. Syringe Volume

	◆ Run #1 Absolute Pressure (kPa)	⧓ Run #1 Syringe Volume (mL)
1	102.7	20
2	116.1	18
3	127.4	16
4	136.3	15
5	146.3	14
6	159.0	13
7	168.8	12
8	180.0	11
9	196.5	10
10		
11		
12		
13		
14		
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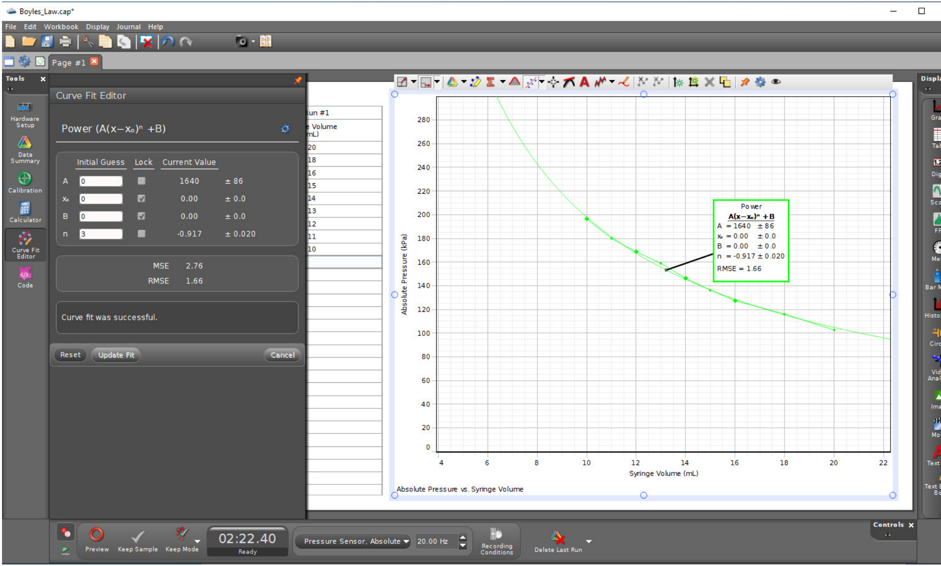
28		

Boyle’s Law for Ideal Gases - 2



Boyles_Law.cap*

Curve Fit Editor

Power (A(x−x₀)ⁿ +B)

	Initial Guess	Lock	Current Value	
A	0	☐	1640	± 86
x₀	0	☑	0.00	± 0.0
B	0	☑	0.00	± 0.0
n	3	☐	-0.917	± 0.020

MSE 2.76

RMSE 1.66

Curve fit was successful.

un #1
e Volume mL)
20
18
16
15
14
13
12
11
10

Power

A(x−x₀)ⁿ +B

A = 1640 ± 86

x₀ = 0.00 ± 0.0

B = 0.00 ± 0.0

n = -0.917 ± 0.020

RMSE = 1.66

Absolute Pressure vs. Syringe Volume

Pressure Sensor, Absolute

20.00 Hz

02:22.40

Ready

Specific Heats of Ideal Gases (The Problem)

Assume that a pure, ideal gas is made of tiny particles that bounce into each other and the walls of their cubic container of side ℓ. Show the average pressure P exerted by this gas is

$$P = \frac{1}{3}\frac{N}{V}m\overline{v_{total}^2}$$

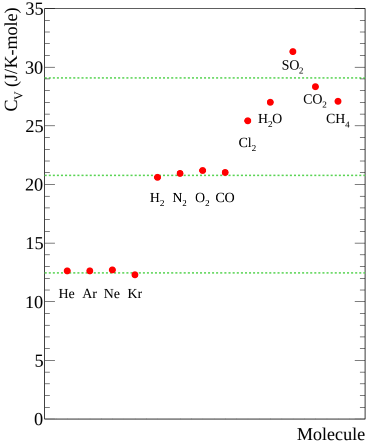
Use the ideal gas law ($PV = Nk_BT = nRT$)and the conservation of energy ($\Delta E_{int} = C_V \Delta T$) to calculate the specific heat of an ideal gas and show the following.

$$C_V = \frac{3}{2}N_A k_B$$

Is this right?

N - number of particles
k_B - Boltzmann constant
N_A - Avogadro's number

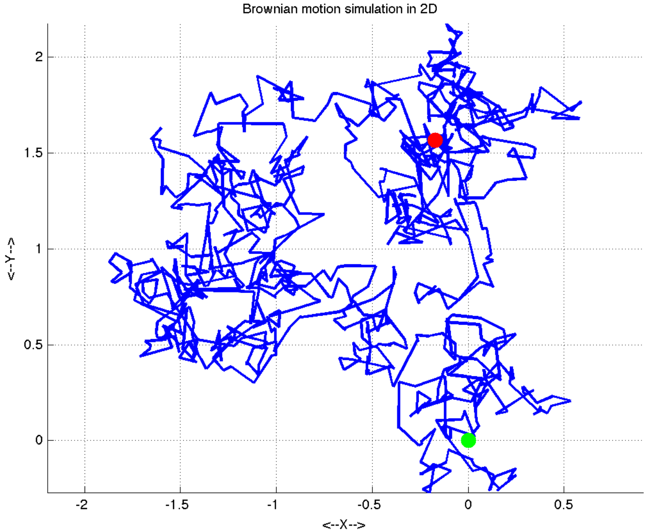
$V = \ell^3$
m - atomic mass
v_{total} - atom's speed



The Kinetic Model of Ideal Gases

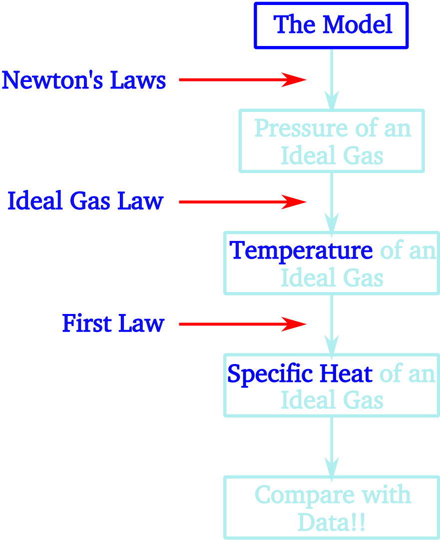
1. The gas consists of a large number of small, mobile particles and their average separation is large.
2. The particles obey Newton's Laws and the conservation laws, but their motion can be described statistically.
3. The particles' collisions are elastic on average.
4. The inter-particle forces are small until they collide.
5. The gas is pure.
6. The gas is in thermal equilibrium with the container walls.

Trajectory of Brownian Motion



Click here

The Plan and the Data



The Model

Newton's Laws

Pressure of an Ideal Gas

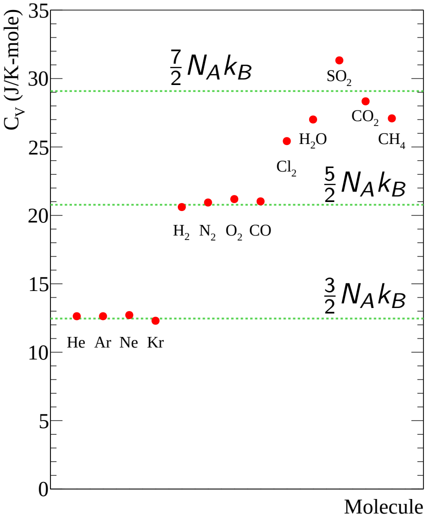
Ideal Gas Law

Temperature of an Ideal Gas

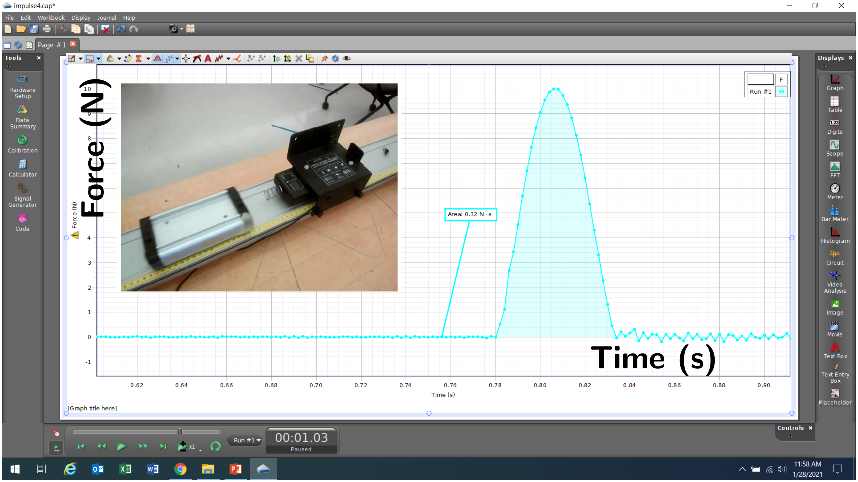
First Law

Specific Heat of an Ideal Gas

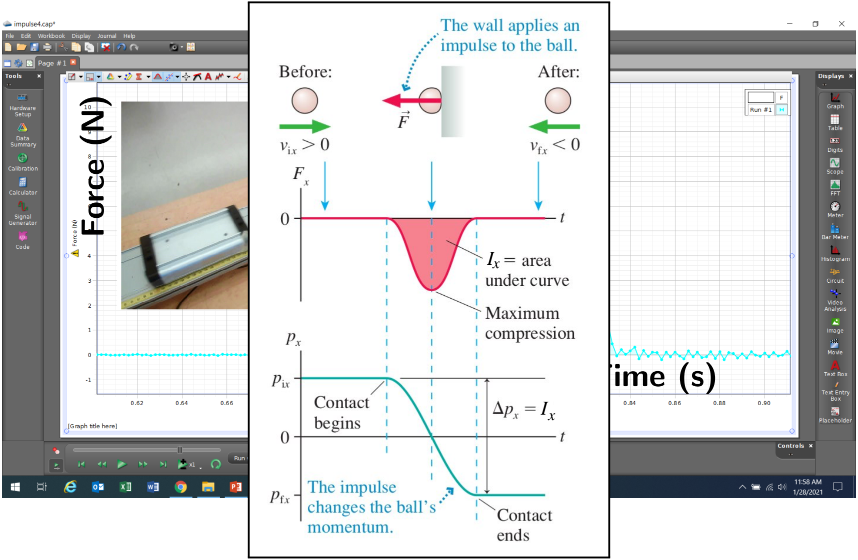
Compare with Data!!



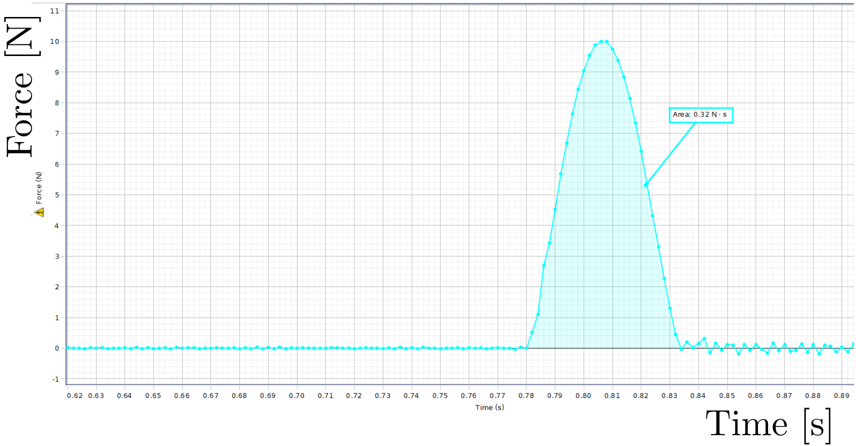
The Pressure of an Ideal Gas - Impulse and Momentum Change 28



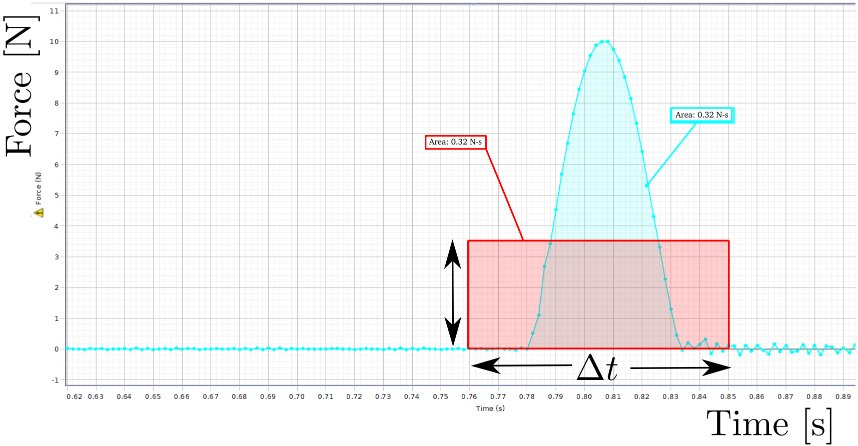
The Pressure of an Ideal Gas - Impulse and Momentum Change



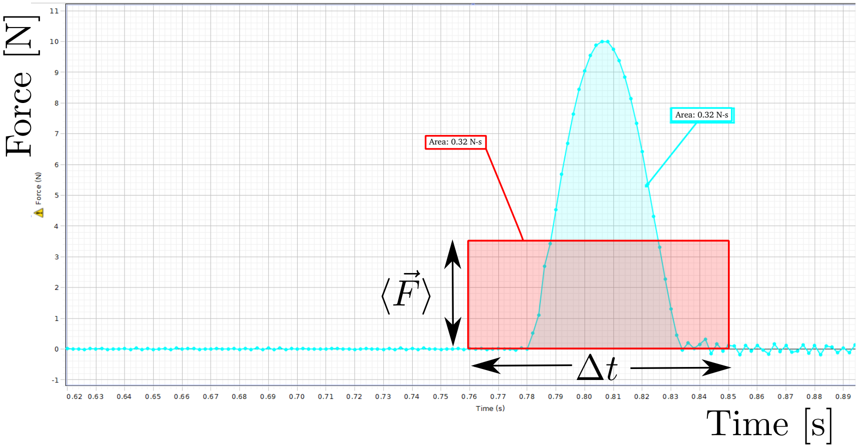
Instantaneous Force



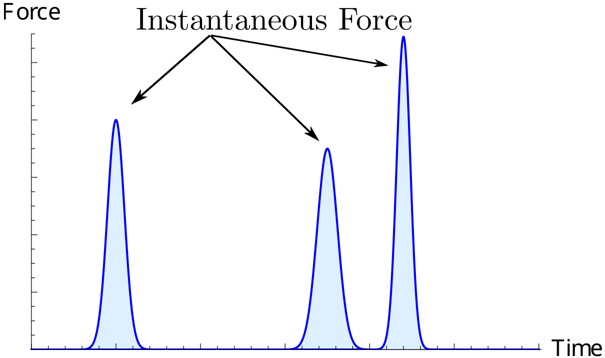
Instantaneous versus Average Force



Instantaneous versus Average Force

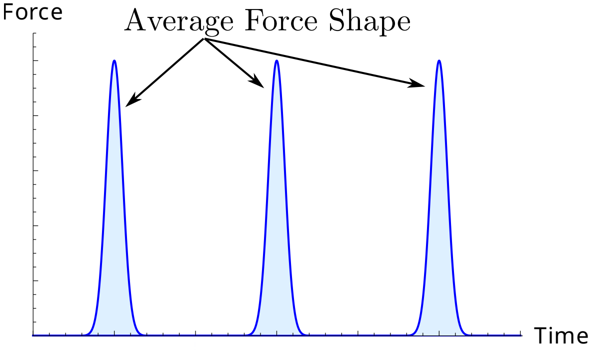


Instantaneous Force in the Gas



1. Consider a tiny patch of the container.
2. It's repeatedly hit by gas particles (blue).

Instantaneous versus Average Force in the Gas



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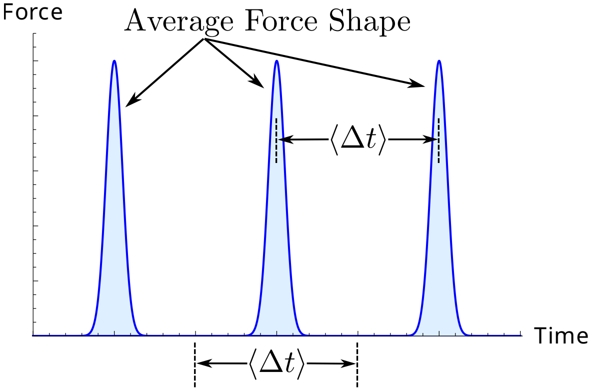
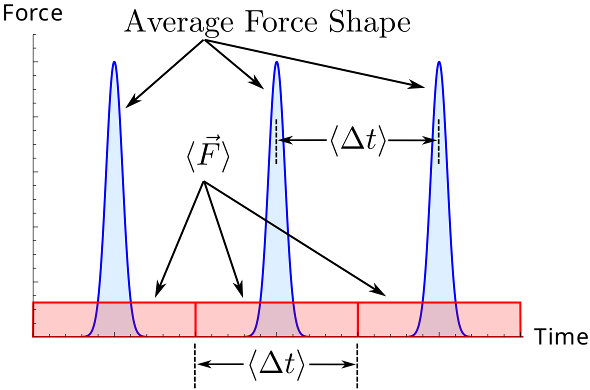
Instantaneous versus Average Force in the Gas



1. Consider a tiny patch of the container.
2. It's repeatedly hit by gas particles (blue).
3. The average time separation is $\langle \Delta t \rangle$.

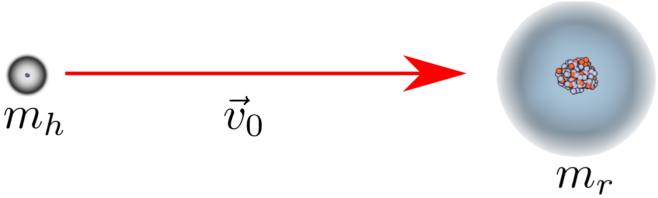
Instantaneous versus Average Force in the Gas



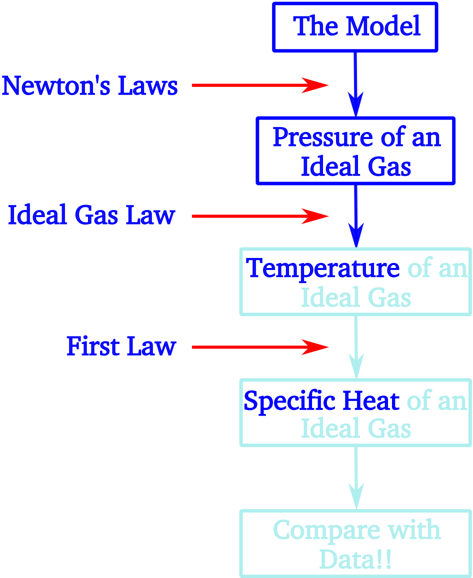
1. Consider a tiny patch of the container.
2. It's repeatedly hit by gas particles (blue).
3. The average time separation is $\langle \Delta t \rangle$.
4. Average force is red.
5. Blue area = Red area

Momentum Conservation and Hitting Walls 37

An atom of mass m_h collides elastically head-on with a heavier, stationary, target atom of mass m_r. Both particles are free to move in space. The initial velocity of the projectile is $\vec{v}_0$ as shown below. What is the final velocity $\vec{v}_1$ of the projectile in terms of the masses, $\vec{v}_0$, and any other constants? What happens to the final velocity $\vec{v}_1$ as the target mass m_r becomes very large? Ignore the effects of potential energy.



The Plan - Act. 2 of *Kinetic Theory of Ideal Gases* 38



The Model

Newton's Laws

Pressure of an Ideal Gas

Ideal Gas Law

Temperature of an Ideal Gas

First Law

Specific Heat of an Ideal Gas

Compare with Data!!

Is Potential Energy Important? 39

A helium atom is moving straight up from the floor of the lab that is at room temperature $T = 300\ K$. Miraculously, the atom never strikes another atom or molecule until it reaches the ceiling at a height $h = 4.0\ m$ above the floor. What is the helium atom's rms speed when it hits the ceiling? How much has its speed changed from the initial speed?

Specific Heats of Ideal Gases

40

Assume that a pure, ideal gas is made of tiny particles that bounce into each other and the walls of their cubic container of side ℓ. Show the average pressure P exerted by this gas is

$$P = \frac{1}{3}\frac{N}{V}m\overline{v_{total}^2}$$

Use the ideal gas law ($PV = Nk_BT = nRT$)and the conservation of energy ($\Delta E_{int} = C_V \Delta T$) to calculate the specific heat of an ideal gas and show the following.

$$C_V = \frac{3}{2}N_A k_B = \frac{3}{2}R$$

Is this right?

N - number of particles

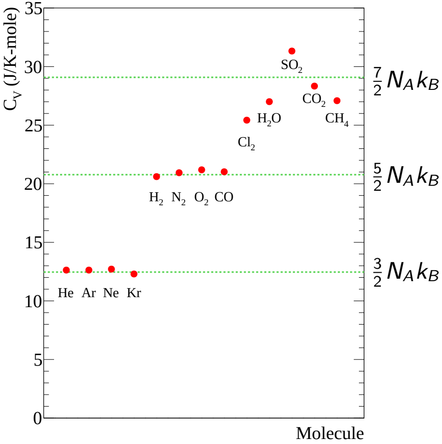
k_B - Boltzmann constant

N_A - Avogadro's number

$V = \ell^3$

m - atomic mass

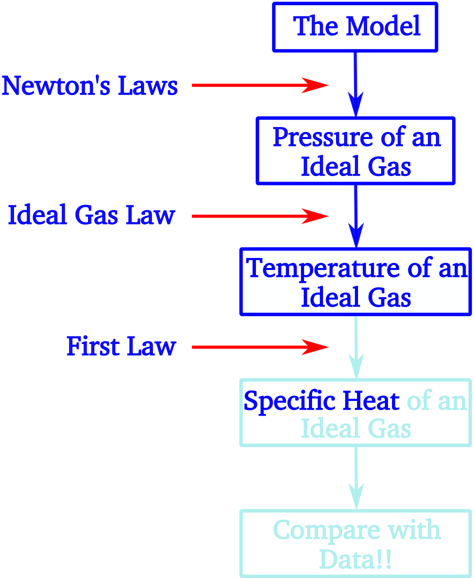
v_{total} - atom's spe



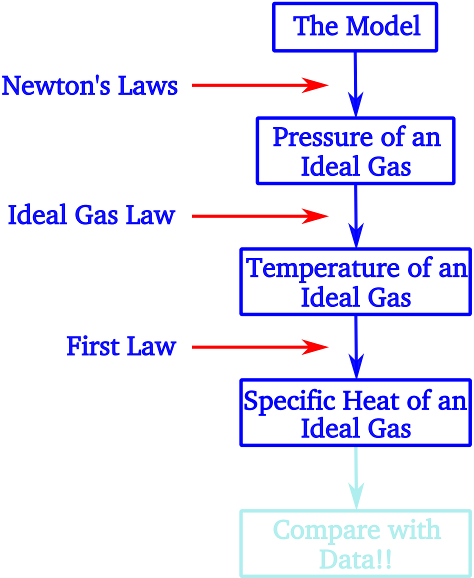
The Kinetic Model of Ideal Gases

1. The gas consists of a large number of small, mobile particles and their average separation is large.
2. The particles obey Newton's Laws and the conservation laws, but their motion can be described statistically.
3. The particles' collisions are elastic on average.
4. The inter-particle forces are small until they collide.
5. The gas is pure.
6. The gas is in thermal equilibrium with the container walls.

The Plan - Activity 2 of *Applying the Kinetic Theory*42



The Plan - Activity 3 of *Applying the Kinetic Theory*43



The Model

Newton's Laws

Pressure of an Ideal Gas

Ideal Gas Law

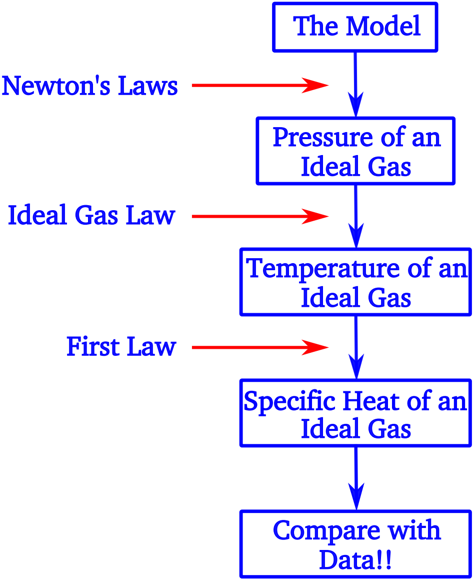
Temperature of an Ideal Gas

First Law

Specific Heat of an Ideal Gas

Compare with Data!!

The Plan - Activity 4 of *Applying the Kinetic Theory*44



The Model

Newton's Laws

Pressure of an Ideal Gas

Ideal Gas Law

Temperature of an Ideal Gas

First Law

Specific Heat of an Ideal Gas

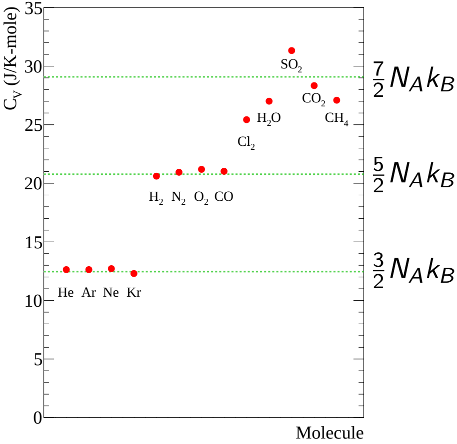
Compare with Data!!

The Results

$$P = \frac{1}{3}\frac{N}{V}m\overline{v_{total}^2} = \frac{2}{3}\frac{N}{V}\langle E_{kin}\rangle$$

$$\langle E_{kin}\rangle = \frac{3}{2}Nk_BT$$

$$C_V = \frac{3}{2}N_Ak_B = \frac{3}{2}R$$



Rotational Kinetic Energy

Classically

$$KE = \frac{1}{2}mv^2 = \frac{m^2v^2}{2m} = \frac{p^2}{2m}$$

For rotational motion

$$E_{rot} = \frac{L^2}{2\mathcal{I}}$$

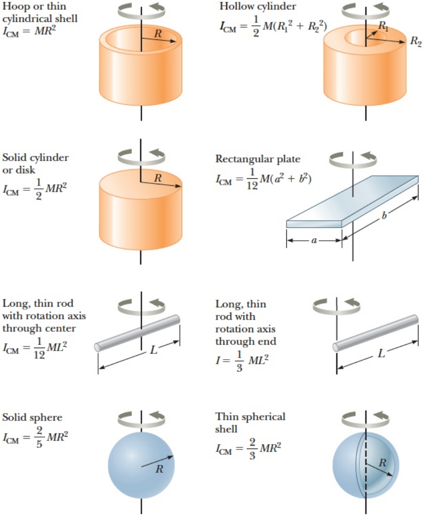
where L is angular momentum and

$$\mathcal{I} = \sum mr_i^2 = \int r^2 dm$$

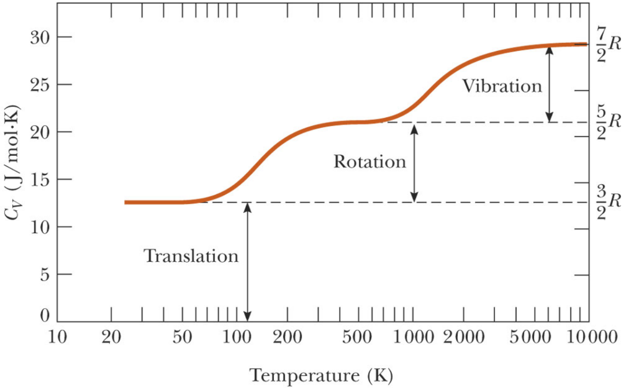
Quantum mechanically

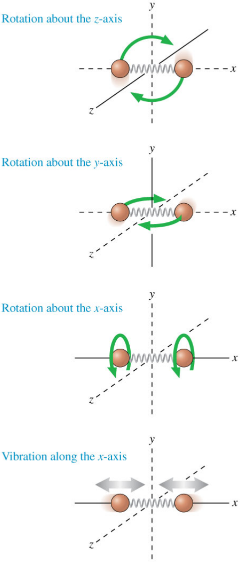
$$E_{rot}^{qm} = \frac{\ell(\ell+1)\hbar^2}{2\mathcal{I}}$$

where ℓ is the angular momentum quantum number.



A Hint of Quantum Mechanics

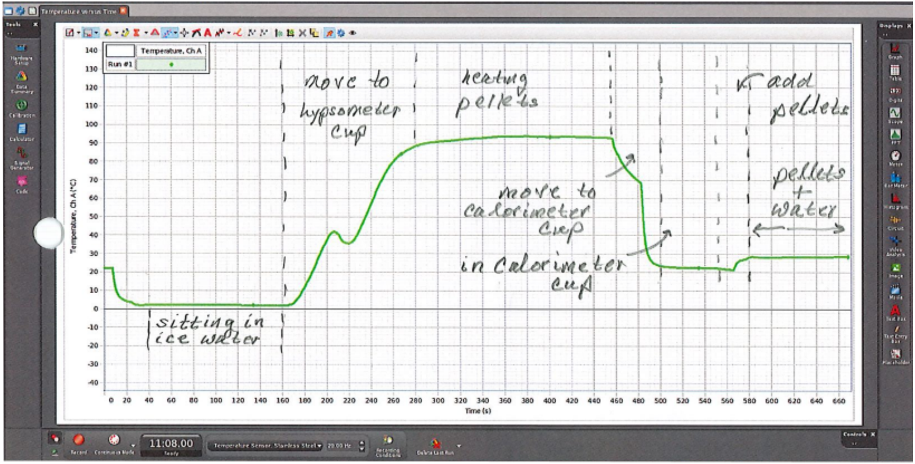




Applying Quantum Mechanics 48

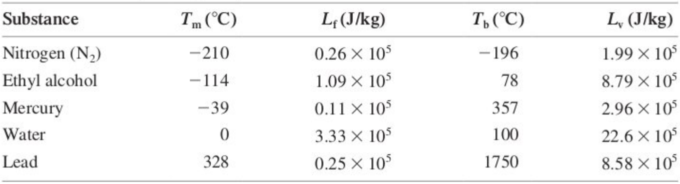
How much heat does it take to increase the temperature of $n = 4.0$ *moles* of $\mathrm{H_2}$ gas by $\Delta \mathrm{T} = 25\ \mathrm{K}$ at room temperature $\mathrm{T} = 25^\circ\mathrm{C}$ if the gas is held at constant volume? Would the answer change if the gas were $\mathrm{N_2}$? What about He?

Calorimetry Measurement



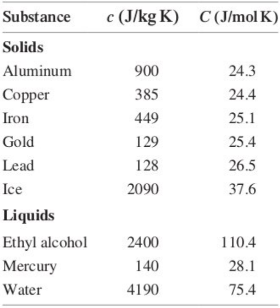
Thermodynamic Information

TABLE 17.3 Melting/boiling temperatures and heats of transformation



Substance	T_m (°C)	L_f (J/kg)	T_b (°C)	L_v (J/kg)
Nitrogen (N_2)	−210	0.26×10^5	−196	1.99×10^5
Ethyl alcohol	−114	1.09×10^5	78	8.79×10^5
Mercury	−39	0.11×10^5	357	2.96×10^5
Water	0	3.33×10^5	100	22.6×10^5
Lead	328	0.25×10^5	1750	8.58×10^5

TABLE 17.2 Specific heats and molar specific heats of solids and liquids



Substance	c (J/kg K)	C (J/mol K)
Solids		
Aluminum	900	24.3
Copper	385	24.4
Iron	449	25.1
Gold	129	25.4
Lead	128	26.5
Ice	2090	37.6
Liquids		
Ethyl alcohol	2400	110.4
Mercury	140	28.1
Water	4190	75.4