Physics 213

Thermal Physics

An Introductory Course in

Thermodynamics and Statistical Mechanics

Welcome to Physics 213

Faculty: Lectures A&B: Paul Kwiat
Discussion: Raffi Budakian
Labs: Alexey Bezryadin

All course information is on the web site. Read it !!
courses.physics.illinois.edu/phys213

Format: Active Learning (Learn from Participation)

- Prelectures: 5-10 for the semester
- Lecture: Presentations, demos, & ACTs. — Bring your calculator.
- Discussion: Group problem solving. — Starts this week
- Homework/Online Quizzes: — The struggle IS the idea.
- Lab: Up close with the phenomena. — Starts next week
  Prelabs are due at the beginning of lab.

Ask the Prof.: online question feature through *SmartPhysics* – it's the "CheckPoint" feature for each lecture.
This Friday only: Bonus point for doing the survey.

Textbook: Wolfe, Elements of Thermal Physics (we will call "Elements")
Reading assignments on Syllabus page

James Scholar Students: See link on course website for information.

WWW and Grading Policy

Almost all course information is on the web site

Here you will find:

- announcements
- syllabus (reading assignments,what we're doing every week) ⇐ Look at it !!
- course description & policies
- lecture slides
- lab information
- discussion solutions (at the end of the week)
- homework assignments
- sample exams
- gradebook.

Need to send us email?
Send it to the right person.
See "contact Info"
on the web page.

The official grading policy: (See the course description for details)

- Your grade is determined by exams, homework, quizzes, labs, and lecture.
- The lowest quiz score will be dropped. No other scores will be dropped.
- Letter grade ranges are listed on the web.
- Excused absence forms must be turned in within one week of your return to class.

If you miss too many labs or quizzes, whether excused or not, you will not get course credit!!

Lectures Use iClickers

See “iClickers” on the web page.

- We’ll award a point for every lecture attended, up to 15 maximum.

  “Attended” ≡ responded to ≥1/2 of questions. We don’t grade your response.

  It doesn’t matter which lecture you attend.
- Batteries: If the battery-low indicator flashes, you still have several lecture’s worth of energy, i.e., *NO iClicker EXCUSES.*
- Everyone will get iClicker credit for lecture 1, so:
  - Don’t worry if you don’t have yours today.
  - Don’t assume that credit in the grade book for lecture 1 means you’ve properly registered (wait ~2 weeks to see).
- Once again: *NO iClicker EXCUSES.*

iClicker Practice

Act 0:

What is your major?

A. Engineering (not physics)
B. Physics
C. Chemistry
D. Other science
E. Something else

NOTE: Everyone will get I-Clicker credit for Lect. 1, so
a. don't worry if you didn't have yours today.
b. don't assume that credit in the gradebook for Lect. 1 means you've properly registered (wait ~2 weeks to see).
Further questions: Phys213-clickers@physics.illinois.edu

An Unfortunate iClicker Complication

The lecture next door also uses iClickers. Unless we use a different frequency, there will be interference. So, we will use frequency BB.

How to change your clicker frequency:

Hold the power button for two seconds (the blue light will flash). Then push B twice. You will get a short green light confirmation.

You will have to do this every time you turn your iClicker on. It does not remember.

Act 0:

What is your major?

A. Engineering (not physics)
B. Physics
C. Chemistry
D. Other science
E. Something else

Three Lectures per Week

Unlike P211 and P212, we have three lectures per week (MWF).

- MW lectures will mostly focus on concepts, ACTS, and demos.

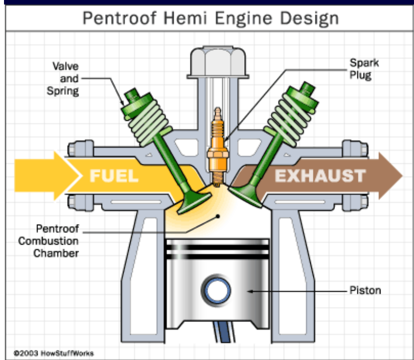
- Friday lectures will focus a bit more on problem solving and question/answer.

If you are confused by something in a MW lecture (and didn't ask during that lecture), ask about it on Friday.

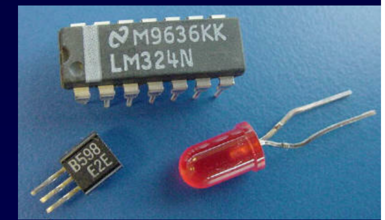
Thermal Physics

You will learn the rules that describe the behavior of:

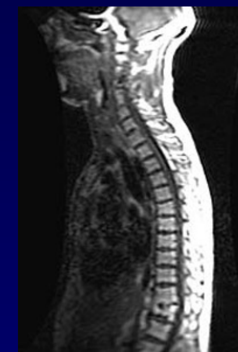
Materials	Phenomena
gases	thermal conduction
liquids	thermal radiation
solids	heat engines
polymers	magnetism



engines



semiconductors



magnetism

Fabrication of materials

biology

chemical reactions

phase transitions

thermal radiation (global warming)

Outline of Topics

		Chapters in "Elements"
Lecture 1	Mechanics ←→ Thermodynamics	1,2
Lectures 2-4	Ideal Gases, Thermal Processes	3,4A-C
Lectures 5-10	Introduction to Statistical Mechanics	5-8
Lectures 11-21	Applications to Mechanical, Physical, Chemical and Biological Systems	9, 4D-F 10-13

About two chapters a week – best to read before lecture.

Intended to be preparation for a variety of different courses in physics, materials science, mechanical engineering, chemistry, electrical engineering, agricultural engineering, ….

Prerequisites

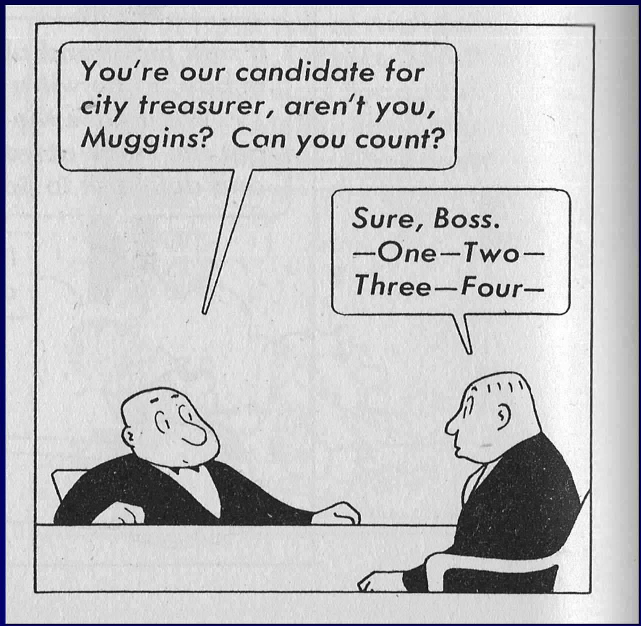
Basic material from Physics 211.

Routine algebra and elementary calculus.

Some chemistry notation. For example:

N_A = Avogadro's # = 6.02×10^{23} molecules/mole

mass of 1 mole in grams = molecular weight (O_2:32g)



We'll do a lot of counting.

Know these facts* by heart:

$$\ln(xy) = \ln(x) + \ln(y) \qquad \ln(e^x) = x = e^{\ln(x)}$$

$$\ln(x/y) = \ln(x) - \ln(y) \qquad \ln(x^N) = N\ln(x) \qquad \ln(1) = 0$$

$$\frac{d}{dx}x^n = nx^{n-1} \qquad \frac{d}{dx}\ln(x) = \frac{1}{x} \qquad \frac{d}{dx}e^{ax} = ae^{ax}$$

$$\int x^n dx = x^{n+1}/(n+1) \qquad \int dx/x = \ln x \qquad \int_{x_o}^{\infty} e^{-ax}dx = \frac{1}{a}e^{-ax_0} \text{ if } a > 0$$

Notation: $\left.\frac{\partial f(x,y)}{\partial x}\right|_y$

We'll also need some multivariable calculus; see Elements, Chap. 2D:

*some other relevant math facts are in the Appendix.

Today

Connection between Mechanics and Thermodynamics

The Language of Mechanics
  Define terms

The Work- Energy equation
  What does and doesn't follow from Newton's Second Law

Inelastic collisions
  Concepts of internal energy and irreversibility

Microscopic description of pressure
  Colllisions of molecules with the walls of a container.

Reading for this Lecture:
Elements Ch 1,2

Reading for Lecture 2:
Elements Ch 2,3

Newton's Laws and Work

For a single object of mass m:

$F = ma = dp/dt \quad \Rightarrow \quad F\,dt = m\,dv = d(mv)$

$F\,v\,dt = m\,v\,dv$

$F\,dx = d(\tfrac{1}{2}mv^2)$

$\int F\,dx = \tfrac{1}{2}mv_f^2 - \tfrac{1}{2}mv_i^2 = \Delta(KE)$

For a system of objects,

$M = \Sigma m_i$ with $F_{tot} = \Sigma F$

$F_{tot} = Ma_{cm} = dp_{cm}/dt \quad \Rightarrow \quad \int F_{tot}\,dx_{cm} = \tfrac{1}{2}mv_{cmf}^2 - \tfrac{1}{2}mv_{cmi}^2 = \Delta(KE_{cm})$

However, $KE_{cm} \neq KE_{tot}$!!! $\quad KE_{tot} = KE_{cm} + KE_{internal}$

Real systems have many x_i, with different F_i on them.

The total work is not $F_{tot}dx_{cm}$ (*e.g.*, torque on a rotating wheel: $F_{tot}=0$)

Energy Dissipation via Friction

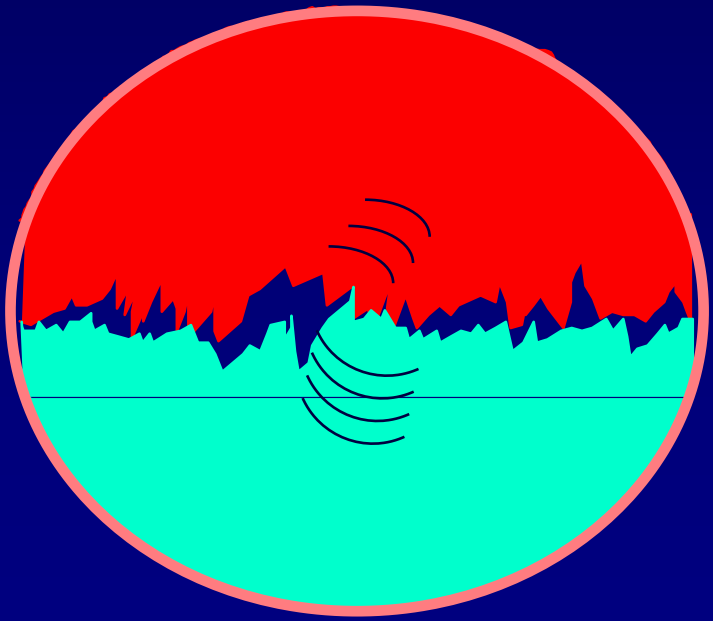
I'm sure this was your favorite P211 topic!

As the parts scrape by each other they start small-scale vibrations, which transfer kinetic and potential energy into atomic motions.

The atoms' vibrations go back and forth. They have energy, but no average momentum.

Random sound waves and heat!

There are so many different forces, F_i, and displacements, dx_i, that there's no way to keep track of the details! Instead, we'll use a statistical analysis.



Work-Energy Equation

Work done on a system = Change of the total energy

$$W_{on} = \Delta(E_{tot})$$

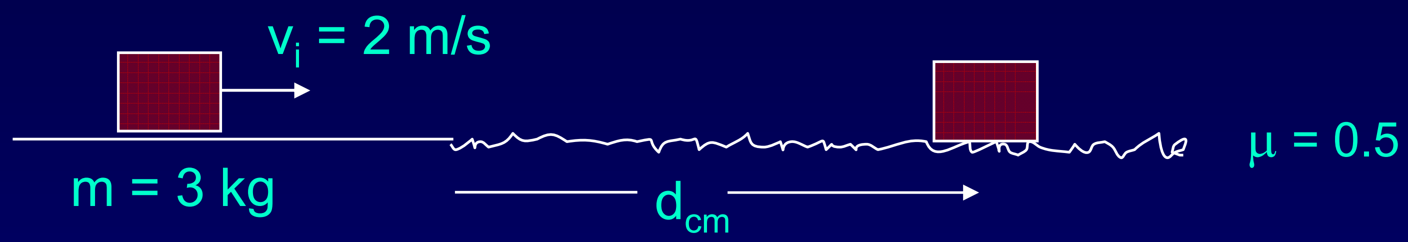
$E_{tot} = (1/2)mv_{cm}^2 + U$

U = internal energy = energy viewed in c.m. frame
(including vibrations, rotations, internal KE and PE)

In this course, we will deal almost exclusively with U.

Example: Friction

Friction is an irreversible process. We will spend a lot of time in this course comparing reversible and irreversible processes.



a) How far does the block go after entering the rough region?

b) How much energy is dissipated as internal vibrations?

Solution

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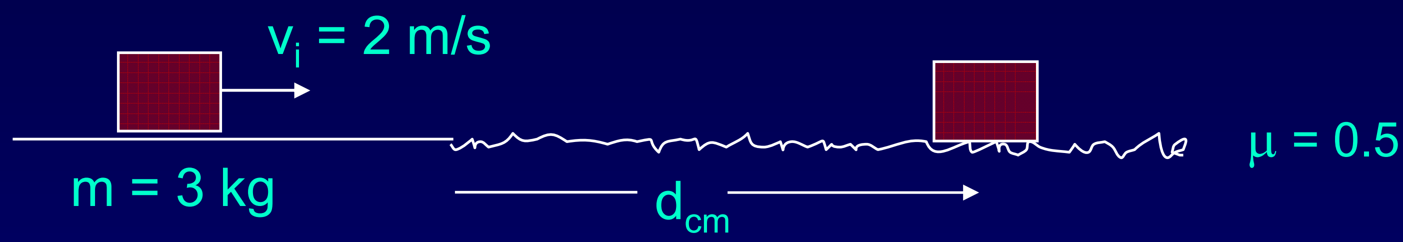


a) How far does the block go after entering the rough region?

$$F \cdot d_{cm} = \Delta(KE_{cm}) = -\tfrac{1}{2} m v_i^2 \Rightarrow \quad d_{cm} = \tfrac{1}{2} v_i^2 / \mu g = 0.41 \text{ meters}$$

$$F = -\mu m g$$

b) How much energy is dissipated as internal vibrations?

Here, "internal" includes the block and the floor, so we must treat them as a single system: $F_{ext} = 0$, so $\Delta E_{tot} = E_f - E_i = 0$.

$$E_i = \tfrac{1}{2} m v_i^2 = E_f = \underbrace{\tfrac{1}{2} m v_f^2}_{=0} + U_{thermal} \quad \Rightarrow \quad U_{thermal} = \tfrac{1}{2} m v_i^2 = 6 \text{ J}$$

Act 1: Dropped Block

A lead block weighing 1 kg is dropped from a height of 1m.
What is the change in thermal energy?

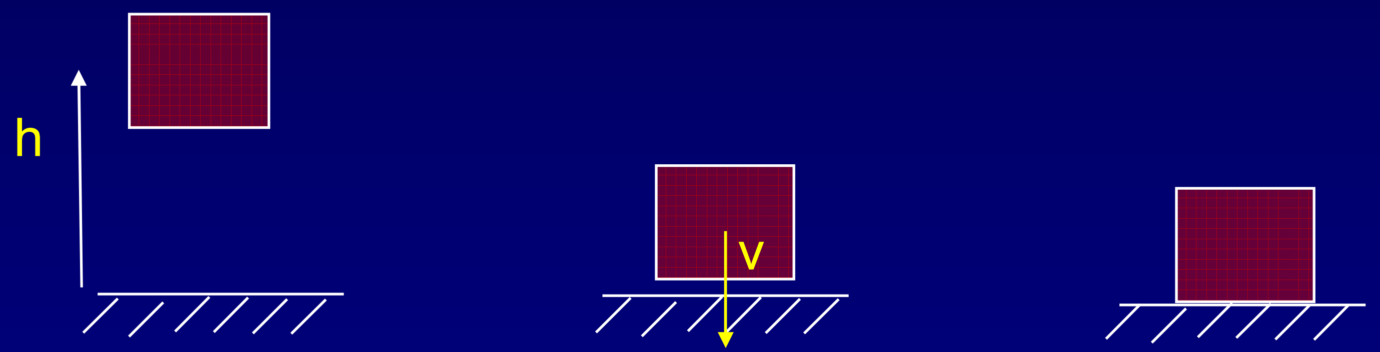
a. 0 b. 4.9 J c. 9.8 J d. cannot be determined

Solution

A lead block weighing 1 kg is dropped from a height of 1m.
What is the change in thermal energy (of the block + floor)?

a. 0 b. 4.9 J $\boxed{\text{c. } 9.8\ \text{J}}$ d. cannot be determined

Block + Earth is an isolated system (W_{on} = 0).
Energy is conserved (E_{tot} = constant):
As time proceeds, the energy changes form:



Start with v = 0
E_{tot} = PE = mgh

mgh = ½ mv^2
v = $(2gh)^{1/2}$

v = 0
mgh = $U_{thermal}$

Potential energy $\rightarrow$ Kinetic energy $\rightarrow$ Thermal energy

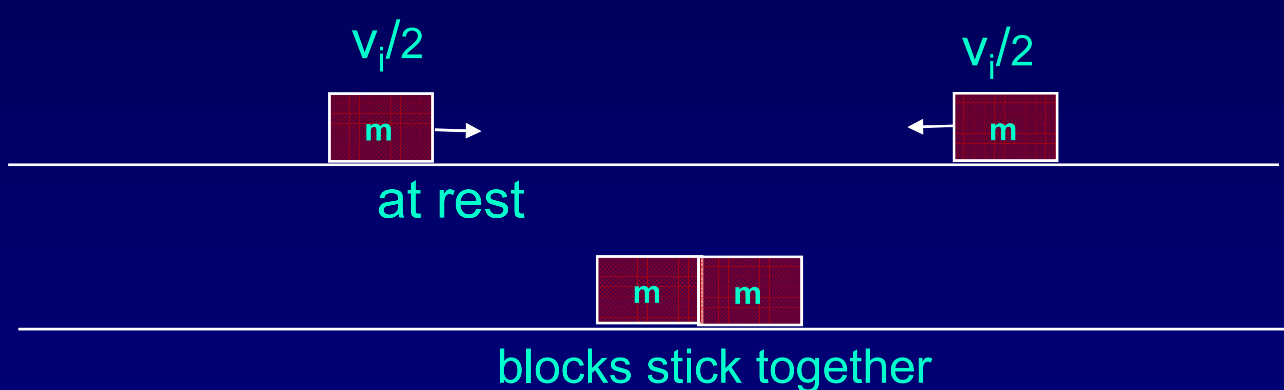
This is an irreversible process

Home exercise: Mechanics example #2:

Inelastic collision of two blocks on a frictionless surface

Isolated system, $\Delta E=\Delta(KE_{cm})=0$, so $\Delta U=0$

Let's view the collision process in c.m. frame:



The easily identifiable kinetic energy is all changed into thermal energy:

$$\boxed{U_{thermal} =}$$

"Irreversible process"

Same result in the Lab frame, slightly harder.

The Flow of Thermal Energy

Thermal energy flows irreversibly from one place to another:

Hot object **Cold object**

Which way does heat flow?

In Physics 211, we saw that many processes are governed by conservation of energy. In this course we call that:

The First Law of Thermodynamics - Energy is conserved.

The first law doesn't tell us the flow direction; energy is conserved either way. We need something new. The new idea is:

The Second Law of Thermodynamics - Total entropy always increases.

The main goal of this course is to understand entropy and its implications. For example, why heat must flow from hot to cold.

Entropy: the One New Concept

We will see that entropy is just a way of measuring probability.

- Most many-particle states look ‘random’ (*e.g.*, atoms in a gas).
- If several possible outcomes each have a known number of ways they can occur, then randomness tells us that the probability of each is simply proportional to the number of ways. Example: Consider the probability of obtaining a “seven” when two dice are rolled.
- The statement that entropy increases is simply the statement that as systems approach thermal equilibrium, they are more likely to be found with the properties that can be achieved the largest number of ways.

The plan:

- We’ll spend two weeks studying the thermal properties of materials, using intuitive notions of randomness.
- Beginning in week 3, we’ll define entropy and show how that concept can be used to solve problems.

Act 2

To illustrate how large, many-particle systems behave, consider a familiar system, the air in this room.

Why does the air spread out to fill the room?

a) The atoms repel each other, so the gas expands to fill up the available space.
b) The atoms move around randomly, so they just end up all over the place by accident.
c) The energy of the system is lowered when the gas fills all the available space.

Solution

To illustrate how large, many-particle systems behave, consider a familiar system, the air in this room.

Why does the air spread out to fill the room?

a) The atoms repel each other, so the gas expands to fill up the available space.

b) $\boxed{\text{The atoms move around randomly, so they just end up all over the place by accident.}}$

c) The energy of the system is lowered when the gas fills all the available space.

The molecules just distribute themselves randomly and quite uniformly. There are simply more ways to spread out the gas than to compress it.

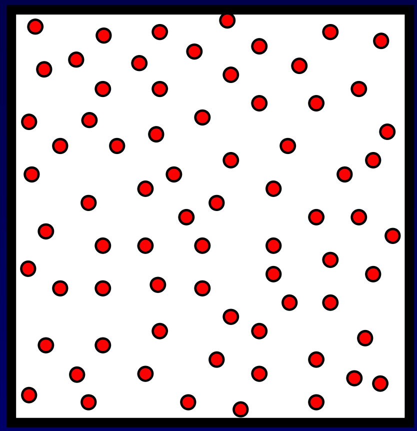
Choices a and c are wrong. In fact, there is a small *attraction* between molecules.

Kinetic Theory of an Ideal Gas

Our goal: Relate temperature and pressure to molecular motion

Microscopic model for a gas:
A collection of molecules or atoms moving around without touching much:

- random velocities
- every direction equally likely
- a distribution of speeds



Ideal gas definition:

- molecules occupy only a small fraction of the volume
- molecules interact so little that the energy is just the sum of the separate energies of the molecule,i.e., no PE from interactions

The atmosphere is nearly ideal, but the working fluid in an air-conditioner is far from ideal, even when it's not liquid.

http://intro.chem.okstate.edu/1314F00/Laboratory/GLP.htm

Pressure

Pressure is the force per unit area exerted by the gas on any wall.

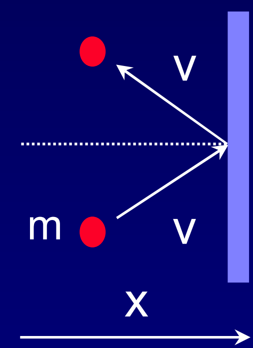
$$p = \frac{F}{A}$$

The force on a wall from gas is the time-averaged momentum transfer due to collisions of the molecules off the walls.

Notation:
<···> means
"time average".

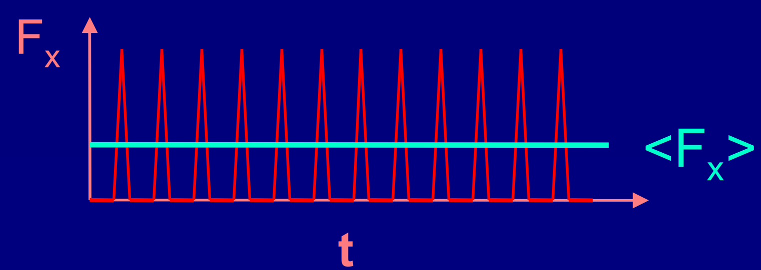
For a single collision:
The x-component changes sign.

$$\Delta p_x = 2mv_x$$



If the time between collisions is Δt, then the average force on the wall due to this particle is:

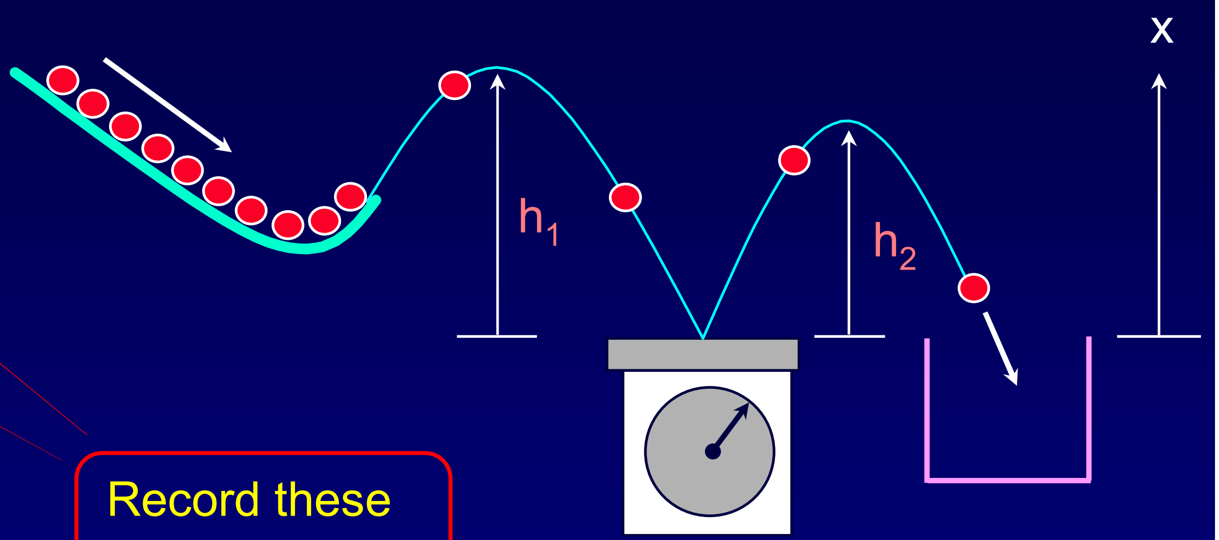
$$\langle F_x \rangle = \frac{2mv_x}{\Delta t}$$



Quantitative Demonstration of Pressure

mass of balls:	m	$= 8.33$ g
# of balls:	N	$= 228$
elapsed time:	Δt	= _____
"weight" (on scale)	F_{av}/g	= _____
Heights:	h_1	$= 2.4$ m
	h_2	= _____

Record these measurements



In discussion, you'll answer these questions:

1. What is v_x just <u>before</u> the balls strike the scale? Just <u>after</u> they strike the scale?
2. What is the momentum transfer to the scale with each collision?
3. What is the average force on the scale as the balls are striking it? Does this agree with the scale reading?

Pressure and Kinetic Energy

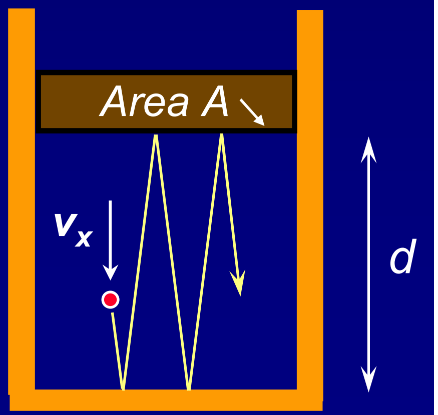
Consider a very sparse gas (no molecule-molecule collisions)

- Time between collisions with a wall (round trip time) $\Delta t = \dfrac{2d}{v_x}$
- Average force (one molecule) $\langle F_x \rangle = \dfrac{2mv_x}{\Delta t} = \dfrac{2mv_x}{(2d/v_x)} = \dfrac{m}{d} v_x^{\ 2}$
- Average force (N molecules) $\langle F_x \rangle = \dfrac{Nm}{d} \langle v_x^{\ 2} \rangle$
- Pressure $p = \dfrac{\langle F_x \rangle}{A} = \dfrac{Nm}{Ad} \langle v_x^{\ 2} \rangle = \dfrac{Nm}{V} \langle v_x^{\ 2} \rangle$
- Relate mv_x^2 to the average translational KE (per molecule)

$$\langle KE_{trans} \rangle = \tfrac{1}{2} m \left\{ \langle v_x^2 \rangle + \langle v_y^2 \rangle + v_z^2 \right\} = \tfrac{3}{2} m \langle v_x^2 \rangle$$

- Therefore, pressure is proportional to the average translational kinetic energy of the gas:

$$\boxed{p = \frac{2}{3} \frac{N}{V} \langle KE_{Trans} \rangle}$$



http://intro.chem.okstate.edu/1314F00/Laboratory/GLP.htm

The Ideal Gas Law

The Pressure-Energy relation: $$p = \frac{2}{3}\frac{N}{V}\langle KE_{TRANS} \rangle$$

Plus the equipartition principle:
(We'll discuss it next lecture.) $$\tfrac{3}{2}kT = KE_{\text{trans}}$$

Combine to give us the ideal gas law: $$\boxed{pV = NkT}$$

The equipartition principle tells us how temperature is related to the distribution of energy among the different modes of motion (translation, rotation, *etc*.) We'll have a lot to say about this.

Appendix: Natural Logarithms

Logarithm of a product is a sum of logarithms:

$\ln(25) = \ln(5^2) = 2\ln(5)$

$\ln(10^{15}) = 15 \ln(10)$

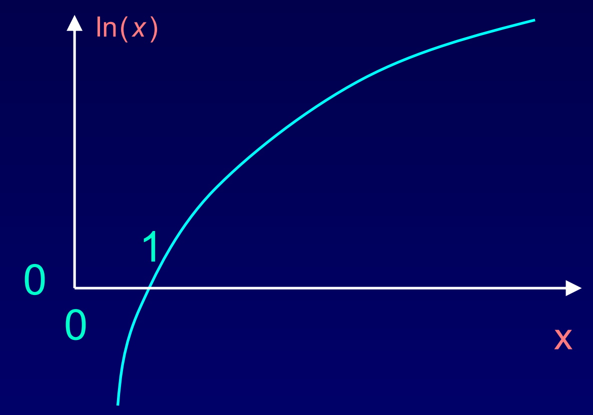
$\ln(10) = 2.303$

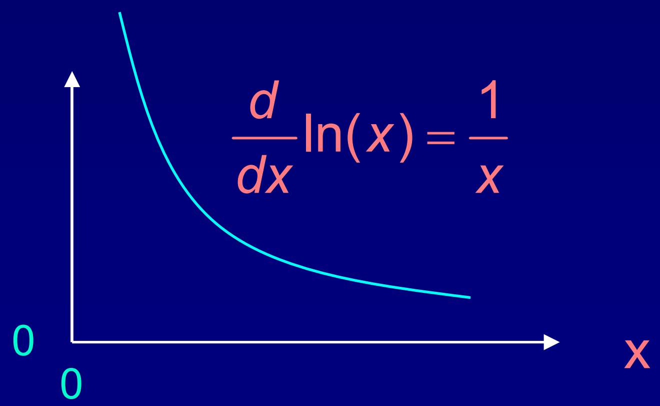
$\ln(1) = 0$

$\ln(50) = 2\ln(5) + \ln(2)$

$\ln(e) = 1$

$e = 2.718$





$$\frac{d}{dx}\ln(x) = \frac{1}{x}$$

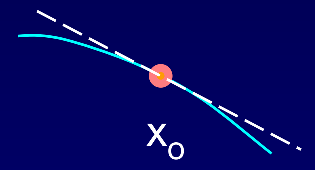
$$\int_{x_1}^{x_2} \frac{dx}{x} = \ln\left(\frac{x_2}{x_1}\right)$$

More Useful Math Facts

Maximum and minimum:

When f(x) is a max or min then df/dx = 0.
Note that if f(x) is a max at x_o, so is ln[f(x)].

Taylor expansion of a function:



$$f(x) = f(x_o) + \frac{df}{dx}\bigg|_{x_o}(x - x_o) + \frac{1}{2}\frac{d^2f}{dx^2}\bigg|_{x_o}(x - x_o)^2 + \cdots$$

Relation of sums to integrals:

$$\sum_n y_n \cdot \Delta x_n \approx \int y(x)dx$$

Simple example: $y(x) = x^2$ $\Delta x_n = 1$

$$\sum_n y_n \cdot \Delta x_n = 1 + 4 + 9 + 16 = 30$$

$$\int x^2 dx = \frac{1}{3}x^3\Big|_{0.5}^{4.5} = \frac{(91.4 - 0.1)}{3} = 30.3$$