Physics 111

Lecture 25

Tuesday, December 7, 2004

• Ch 17: Kinetic Theory
  Stress
  Strain

• Ch 18: 1st Law of Thermodynamics
  2nd Law of Thermodynamics

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Announcements

The Physics 111 Help Session

For the rest of the semester

• Thursday, Dec. 9, 3 - 5pm and 7 - 9pm

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Announcements

Tues. Dec. 7.

Last Lab Meets This Week

Don’t forget to prepare for a short quiz.

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Announcements

Tues. Dec. 7.

Announcements

Monday, Dec. 13, 2004
10:30 am – 12:30 pm everything

• Part 1: Fluids & Thermodynamics
  3 sections - you choose 2
  7.5% of overall final grade

  topics covered:
  radiation
  calorimetry
  fluids

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Announcements

Monday, Dec. 13, 2004
10:30 am – 12:30 pm everything

• Part 2: Cumulative
  5 sections - you chose 3
  1 multiple choice section (required)
  4 other sections, one of them essay - you choose 2
  15% of overall final grade

  topics covered:
  MC (everything), graphing, kinematics
  Newton’s Laws, work, energy, collisions
  oscillations, thermodynamics
Molecular Understanding of Pressure & Temperature

Equating the right-hand sides of these equations we get

\[ T = \frac{2}{3k_B}(\frac{1}{2}m < v^2 >) \quad \text{OR} \quad \frac{3}{2}k_B T = \frac{1}{2}m < v^2 > \]

We now see directly the relationship between Temperature and molecular kinetic energy.

Recall that \( v_x^2 \quad v_z^2 \)

So \( \frac{1}{2}m < v_x^2 > = \frac{1}{2} k_BT \)

This result implies that 1/3 or the kinetic energy (on average) can be found in each direction the gas molecules are allowed to move. We call these directions in which the molecules may move “degrees of freedom”—i.e., the number of ways in which a molecule is free to move.

Molecular Understanding of Pressure & Temperature

Equipartition Theorem

Energy is equally divided among the available degrees of freedom for a system in thermal equilibrium.

This theorem implies that the total energy of a 3-D gas with \( N \) molecules is given by

\[ E_{tot} = N(\frac{1}{2}m < v^2 >) = \frac{3}{2} Nk_BT = \frac{3}{2} nRT \]

\( M \) is the mass per mole

How would the rms speed of the molecules in a gas change if the pressure of the gas was doubled while the volume was kept constant?

1) increase a factor of 4  
2) increase by a factor of 2  
3) increase by a factor of 1.4  
4) stay the same  
5) decrease by a factor of 1.4  
6) decrease by a factor of 2  
7) decrease by a factor of 4

Stress on an object results in strain.

A stress results when a force is applied across a surface of a given object. Stresses result in deformations of the object known as strains.
We push on a piece of copper with a force $F$. If we apply the force over the entire cross-sectional area of the end of the tube, the stress is given by

$$\text{stress} = \frac{F}{A}$$

What happens to real objects when we exert stress such as applied in this figure?

In this case, the copper rod will be compressed. The fractional change in its length is known as the strain:

$$\text{strain} = \frac{\Delta l}{l}$$

When stresses are applied, objects undergo strain. The ratio of the stress to the strain turns out to be a characteristic of the material from which the object is made.

We call the property of a material related to the way it strains under stress...

Young's Modulus

$$Y \equiv \frac{\text{stress}}{\text{strain}} = \frac{F}{A} \frac{A}{\Delta l} = \frac{F}{\Delta l}$$

Notice that Young's modulus will have the same units as stress: $N/m^2$.

We've looked at compressive stress. What happens when we try to stretch an object instead of trying to compress it?

We name the stress that tries to pull an object apart the “tensile stress.”

Again, the ratio of the stress to the strain is still a characteristic of the material from which the object is made.

In fact, Young's modulus describes tensile stress as well as compressive stress.
We can conceive of yet another way to try to deform our copper tube...

Shear stress tries to move one end of the tube in one direction and the other end in the opposite direction!

Unfortunately... shear stress is NOT characterized by Young's modulus...

Let's look at a side view of what happens to our copper cylinder under the influence of shear stress.

Shear stresses produce shear strains

\[
\text{shear stress} = \frac{F}{A}
\]

where \( A \) is the area of the top of the cylinder.

The manner in which an object responds to shear stresses is also a characteristic of the material from which it's made.

Here, we define the ratio of the shear stress to the shear strain as the shear modulus:

\[
S = \frac{\text{shear stress}}{\text{shear strain}} = \frac{F_s}{A} / \frac{\Delta x}{l}
\]

This quantity has the same units as Young's modulus: N/m².

A child slides across a floor in a pair of rubber-soled shoes. The frictional force acting on each foot is 20 N, the cross-sectional area of each foot is 14 cm², and the thickness of the soles is 5 mm. Find the horizontal displacement of the bottom of the soles relative to the top of the soles. The shear modulus for rubber is \( 3.0 \times 10^6 \) N/m².

To end the semester, we take a quick look at the first, second, and third laws of thermodynamics, and what they mean for life in the modern world.
Let’s approach the 1st Law from the perspective of energy conservation.

We spent a fair bit of time developing an understanding of pressure and temperature using kinetic theory.

We now know that an object at a temperature $T$ has an associated thermal energy. For a container of an ideal, monatomic gas, we saw the average kinetic energy per molecule is $\langle K \rangle = \frac{3}{2} k_B T$.

We can approach the 1st Law from the perspective of energy conservation.

If our container has $N$ molecules of this gas in it, then the total kinetic energy of the molecules inside is given by:

$$E_{th} = \frac{3}{2} N k_B T$$

This energy is called the “internal energy” or “thermal energy” of the gas. I’ll use the latter term and stick with $E_{th}$ to represent it.

Let’s approach the 1st Law from the perspective of energy conservation.

Recall the work - kinetic energy theorem

$$W_{net} = \Delta K$$

The net work can be represented by two terms, one for the work done by conservative forces on the system and the other for work done by non-conservative forces on the system:

$$W_{cons} \quad W_{nc} \quad \Delta K$$

Work done by conservative forces can be written in terms of the potential energy function

$$-\Delta U \quad W_{nc} \quad \Delta K$$

...or in the more familiar form

$$W_{nc} = \Delta K + \Delta U$$

Work done on the system changes the system’s kinetic energy, potential energy, or both.

Let’s approach the 1st Law from the perspective of energy conservation.

It’s helpful to think of this equation macroscopically, breaking the thermal energy term away from the kinetic energy. If we do that, then we can rewrite our equation as

$$W_{nc} \quad \Delta K_{cm} \quad \Delta E_{th} \quad \Delta U_{cm}$$

This formulation allows me to separate the thermal motion from the motion of the system.

This red can contains a monatomic ideal gas at temperature $T$ with mass $m$ at an initial height $h$. I then throw the can with initial velocity $v$. 

[Diagram of a red cannister]
Let's approach the 1st Law from the perspective of energy conservation.

Life would be pretty hard right now if I tried to keep track of the potential and kinetic energy of every molecule inside. **YIKES.** But, using that thermal energy term, life is a lot simpler. I can use the kinematics I already know and the thermodynamics I'm learning to keep track of all the different forms of energy.

Let's approach the 1st Law from the perspective of energy conservation.

<table>
<thead>
<tr>
<th>$W_{nc}$</th>
<th>$Q$</th>
<th>$\Delta K_{cm}$</th>
<th>$\Delta E_{th}$</th>
<th>$\Delta U_{cm}$</th>
</tr>
</thead>
</table>

Now, most of the thermodynamics problems won't be nearly so interesting as a launched can of monatomic gas with a bunsen burner attached.

For all of the ideal gas systems we're going to study in thermodynamics, the $\Delta K_{cm} = 0$ and $\Delta U_{cm} = 0$.

1st Law of Thermodynamics

$$\Delta E_{th} = Q - W$$

So, you see, the 1st Law of Thermodynamics comes from a special case of the energy conservation formulation we already know and love!

Just remember to add back the kinetic and potential energy terms on the left-hand side of the equation if you've got a moving, macroscopic system as well.

Let's approach the 1st Law from the perspective of energy conservation.

Clearly I could put my canister on the stove top and witness the temperature increase in the gas inside, yet there's no work being done on the gas.

So we're still missing an energy transfer, about which we just learned last week: heat.

The heat transferred into the system goes on the same side as the work done on the system.

$W_{nc} - W_{sys} = \Delta E_{th}$

With one change, we have arrived at the first law of thermodynamics. In thermodynamics, we talk about the work done BY the system on the environment ($W_{nc}$) rather than the work done ON the system by the environment ($W_{sys}$).

Break up into 5 groups of ~ 4 students each. Each group will tackle on of the following scenarios, evaluating the $W$, $Q$, $\Delta K_{cm}$, $\Delta U_{cm}$, $\Delta E_{th}$, and $\Delta T$ for each system.

1: a steel block slides to rest as it moves up a rough, inclined surface
2: a rigid cylinder of an ideal gas is held still in a flame
3: an expanding spring pushes a rigid cylinder of gas across a frictionless surface
4: an expanding spring pushes in a piston on a well-insulated cylinder of gas
5: a steel block is held at rest in a flame.
Work Done by Ideal Gas Systems

First, a few simplifying assumptions:

Quasi-static: the process occurs slowly enough that the system and its surroundings are always in thermal equilibrium.

Reversibility: the system and its surroundings must return to exactly the same states in which they were before the process.

Processes involving friction are irreversible.

Work Done by Ideal Gas Systems

Use a P-V diagram.

The work done equals the area under the curve.

Plot the values of pressure and volume as the gas energy is exchanged between the gas and its surrounding environment.

P-V diagrams:

Isobaric: Constant pressure processes

In order for a gas to maintain a constant pressure while exchanging heat with its environment, the volume must change.

\[ W = P \Delta V \]

W = PΔV

Isochoric: Constant volume processes

Here, the pressure in the gas changes in response to the heat fluxes, but the gas does no work since the volume is constant.

\[ W = 0 \]

W = 0

From the 1st Law, we then know that the change in thermal energy of the system equals the heat flux into the system:

\[ Q = \Delta E_{th} \]
The P-V diagram below shows two processes, both of which start at the same pressure and volume and end at the same pressure and volume. How does the work done by the gas in process A compare to that done in process B?

Worksheet #5

1) \( W_A = W_B = 0 \)
2) \( W_A = W_B < 0 \)
3) \( W_A > W_B \)
4) \( W_A < W_B \)
5) Need more information

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Work Done by Ideal Gas Systems

Isothermal: Constant temperature processes

Using calculus, we find that the area under such curves, and hence, the work done by the system, is given by

\[ W = Nk_B T \ln \left( \frac{V_f}{V_i} \right) \]

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A cylinder contains 7.0 g of diatomic nitrogen gas. How much work does this gas do on its surroundings when it is compressed to half its original volume at a constant temperature of 80°C?

Worksheet #6