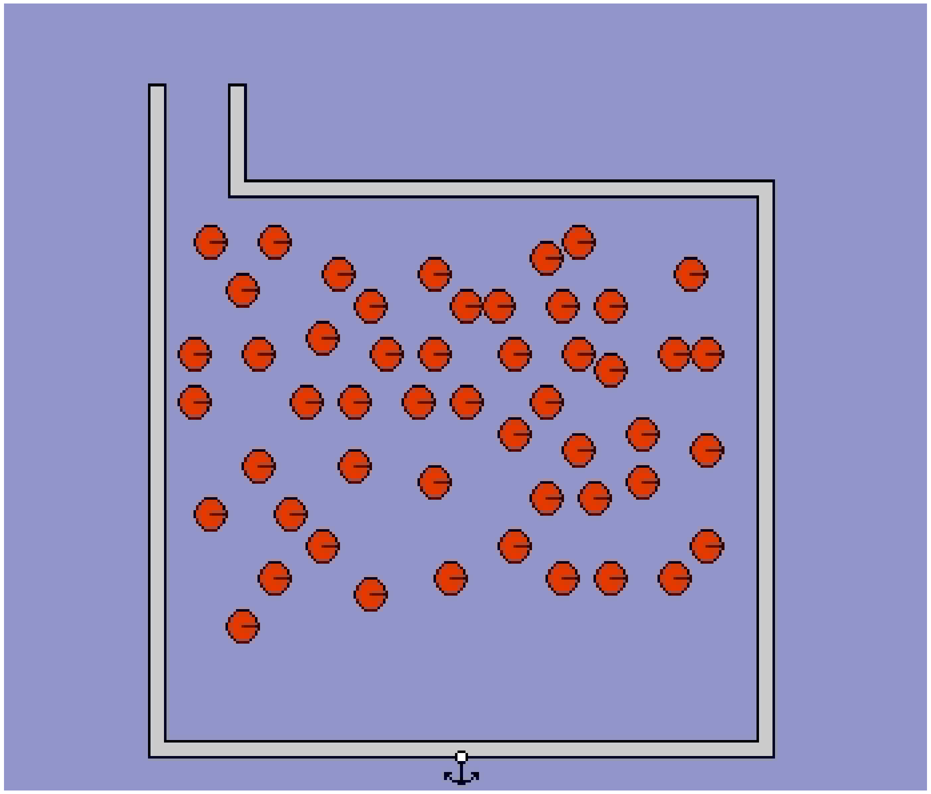
Red Sox - Yankees. Baseball can not get more exciting than these games.

Physics 121, April 17, 2008.
Kinetic theory of gases.



http://eml.ou.edu/Physics/module/thermal/ketcher/Idg4.avi

Physics 121.
April 17, 2008.

- Course Information
- Topics to be discussed today:
  - The ideal gas law (review).
  - Molecular interpretation of temperature.
  - The real equation of state.
- Quiz

Physics 121.
April 17, 2008.

- Homework set # 9 is due on Saturday morning, April 19, at 8.30 am.
- Midterm Exam # 3 will take place on Tuesday April 22 between 8.00 am and 9.30 am. The material to be covered is the material contained in Chapters 10, 11, 12, and 14.
- I will distribute the formula sheet that will be attached to the exam later this week via email.
- I will review the material covered on the exam on Sunday evening. Further details will be announced via email.
- Extra office hours will be offered by the TAs on Sunday and Monday. The schedule will be announced via email.

- **There will be no class after the exam on Tuesday.**

Physics 121.
April 17, 2008.

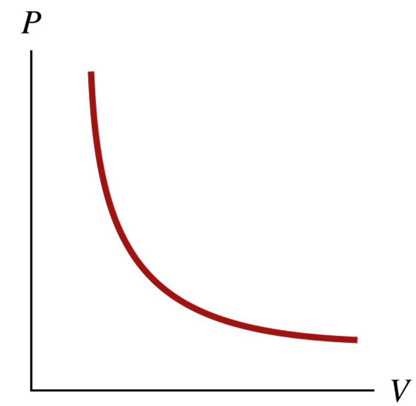
- Workshops schedule next week:
  - There will be workshops on Monday to answer questions related to Exam # 3.
  - There will be workshops on Thursday and Friday to discuss the solutions of Exam # 3 and return your blue booklets.
  - During the week of April 28 there will only be workshops on Monday, Tuesday, and Wednesday.
- To increase the efficiency with which we can return the blue booklets of Exam # 3, you will need to write your workshop day/time on the front of each booklet.
- The results of Exam # 3 will be emailed to you on Monday April 28

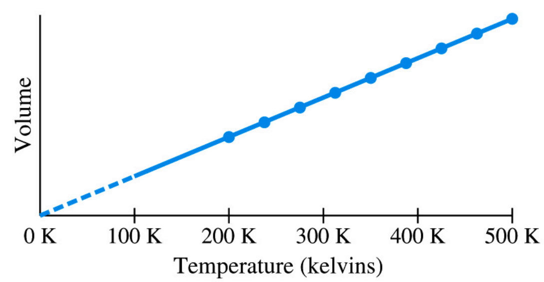
Physics 121.
April 17, 2008.

- Grades: Worst case scenario:
  - Let's assume you got 0% on exam 1 and 0% on exams 2.
  - Clearly you would benefit if we drop one of these grades!
  - If we drop one of these grades, than the one we count will count for 20% of your final grade.
  - If you get 100% on exam # 3 and 100% on the final (and assuming you have 100% on the homework sets, quizzes, and labs) you end up with a final grade for 80% or an A!!!!!
  - No one matches this worst case scenario, but realize that even if you did poorly on the first two exams, you can still get an A in this course.

The equation of state of a gas.
A quick review.

- The equation of state of a gas was initially obtained on the basis of observations.
  - Boyle's Law (1627 - 1691): ***pV* = constant** for gases maintained at constant temperature.
  - Charle's Law (1746 - 1823): ***V/T* = constant** for gases maintained at constant pressure.
  - Gay-Lussac's Law (1778 - 1850): ***p/T* = constant** for gases maintained at constant volume





(b)

The equation of state of a gas. A quick review.

- The equation of state of a gas can be written as

$$pV = nRT$$

where

  - p = pressure (in Pa).
  - V = volume (in m^3).
  - n = number of moles of gas (1 mole = 6.02×10^{23} molecules or atoms). Note the number of molecules in a mole is also known as Avogadro's number N_A.
  - R = the universal gas constant (R = 8.315 J/(mol K).
  - T = temperature (in K).

- Note: the equation of state is the equation of state of an ideal gas. Gases at very high pressure and/or close to the freezing point show deviations from the ideal gas law.

The equation of state of a gas. A quick review.

- The equation of state of a gas can also be written as

$$pV = nRT = (N/N_A)RT = NkT$$

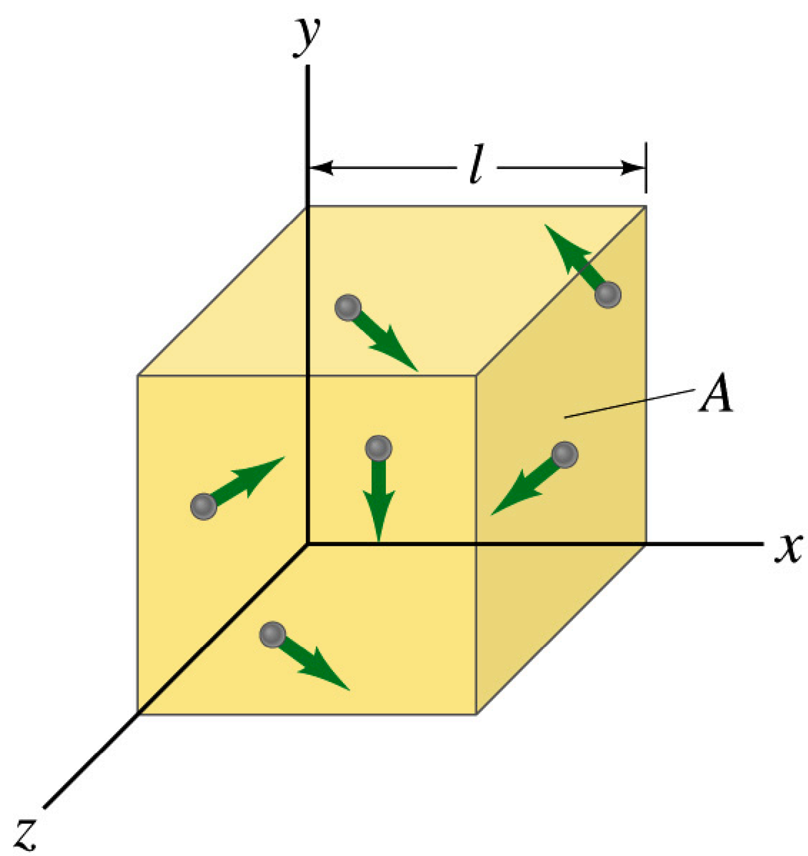
  where

  - N = total number of molecules
  - N_A = Avogadro's number
  - $k = R/ N_A$ is the Boltzmann constant = 1.38×10^{-23} J/K

- This is the most frequently used form of the equation of state of the gas.

The molecular point of view of a gas.

- Consider a gas contained in a container.
- The molecules in the gas will continuously collide with the walls of the vessel.
- Each time a molecule collides with the wall, it will carry out an elastic collision.
- Since the linear momentum of the molecule is changed, the linear momentum of the wall will change too.
- Since force is equal to the change in linear momentum per unit time, the gas will exert a force on the walls.



The molecular point of view of a gas.

- Consider the collision of a single molecule with the left wall.
- In this collision, the linear momentum of the molecule changes by

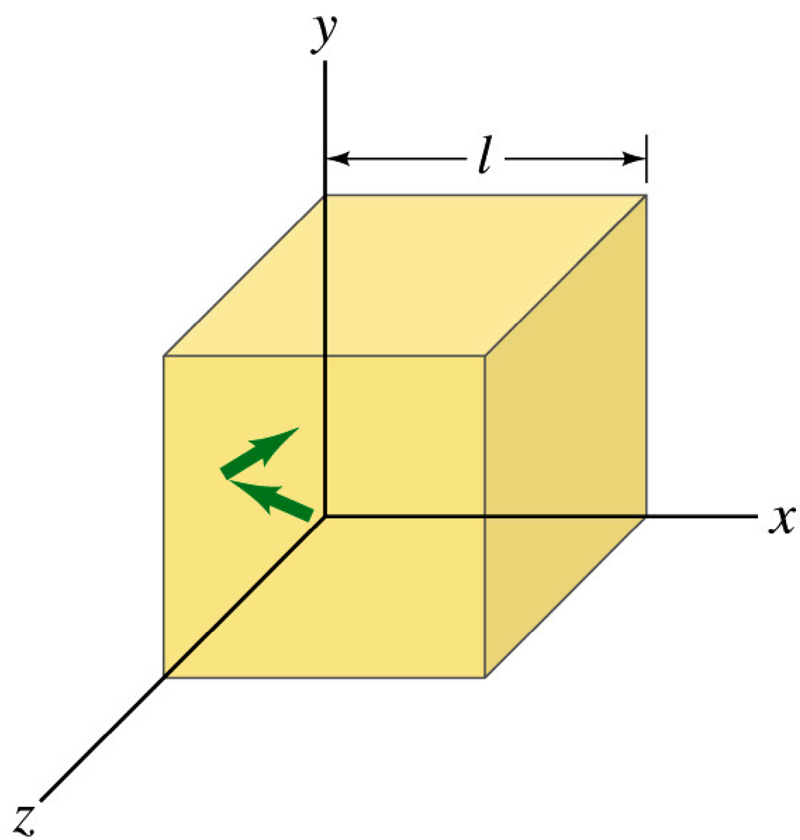
$$mv_x - (-mv_x) = 2mv_x$$

- The same molecule will collide with this wall again after a time

$$\Delta t = 2l/v_x$$

- The force that this single molecule exerts on the left wall is thus equal to

$$\Delta p/\Delta t = (2mv_x)/(2l/v_x) = mv_x^2/l$$



The molecular point of view of a gas.

- The force that this single molecule exerts on the left wall is thus equal to

$$F_{\text{left}} = mv_x^2/l$$

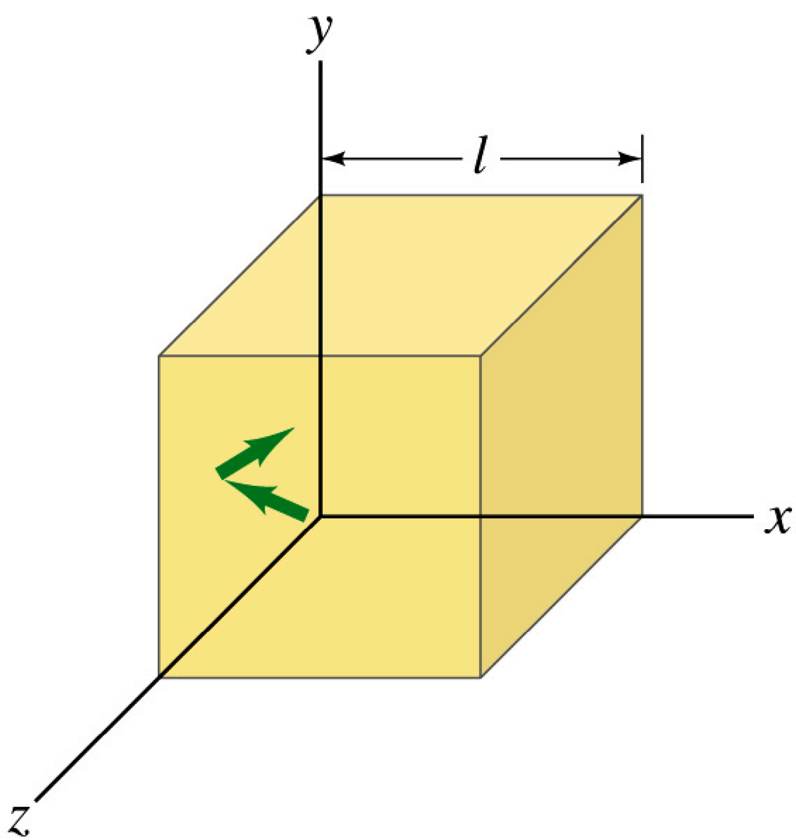
- If the pressure exerted on the left wall by this molecule is equal to

$$p_{\text{left}} = F_{\text{left}}/A = mv_x^2/(lA)$$

where A is the area of the left wall.

- The volume of the gas is equal to lA and we can thus rewrite the pressure on the left wall:

$$p_{\text{left}} = mv_x^2/V$$



The molecular point of view of a gas.

- The pressure that many molecules exerts on the left wall is equal to

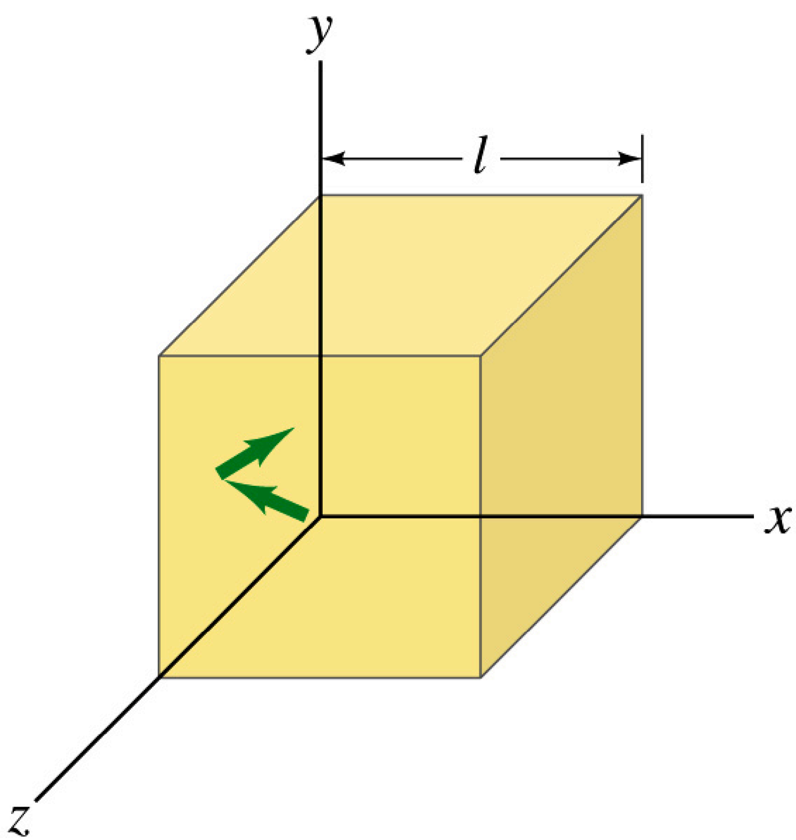
$$p_{left} = m(v_{1x}^2+v_{2x}^2+v_{3x}^2+\dots)/V$$

- This equation can be rewritten in terms of the average of the square of the x component of the molecular velocity and the number of molecules (N):

$$p_{left} = mN(v_x^2)_{average}/V$$

- Assuming that there is no preferential direction, the average square of the x, y, and z components of the molecular velocity will be the same:

$$(v_x^2)_{average} = (v_y^2)_{average} = (v_z^2)_{average}$$



The molecular point of view of a gas.

- The force on the left wall can be rewritten in terms of the average squared velocity

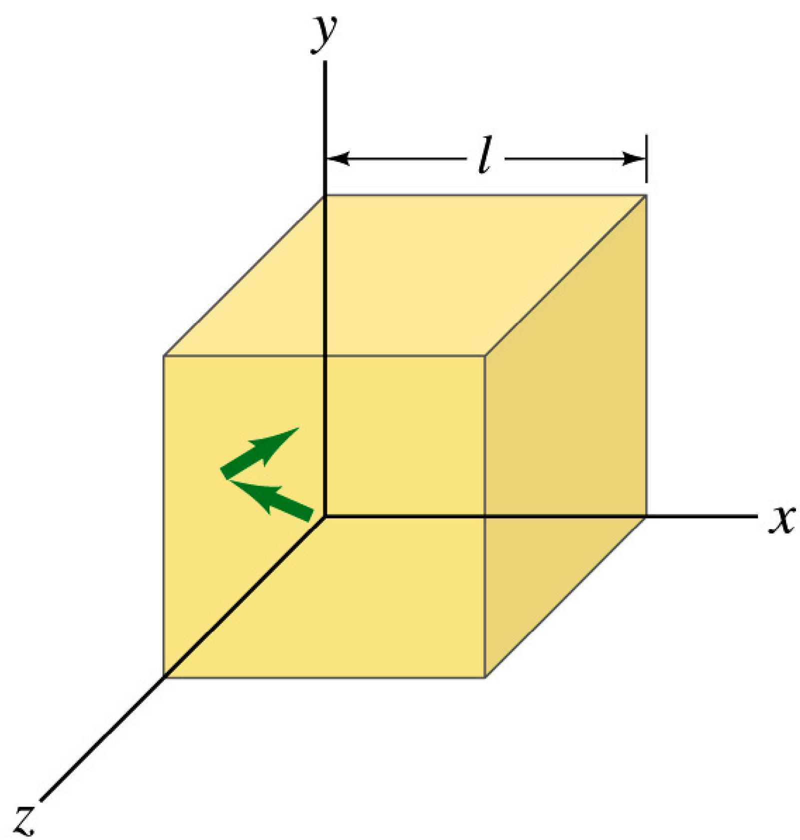
$$p_{\text{left}} = mN(v^2)_{\text{average}}/3V$$

- Assuming there is no preferential direction of motion of the molecules, the pressure on all walls will be the same and we thus conclude:

$$pV = mN(v^2)_{\text{average}}/3$$

- Compare this to the ideal gas law:

$$pV = NkT$$



The molecular point of view of a gas.

- Comparing

$$pV = mN(v^2)_{\text{average}}/3$$

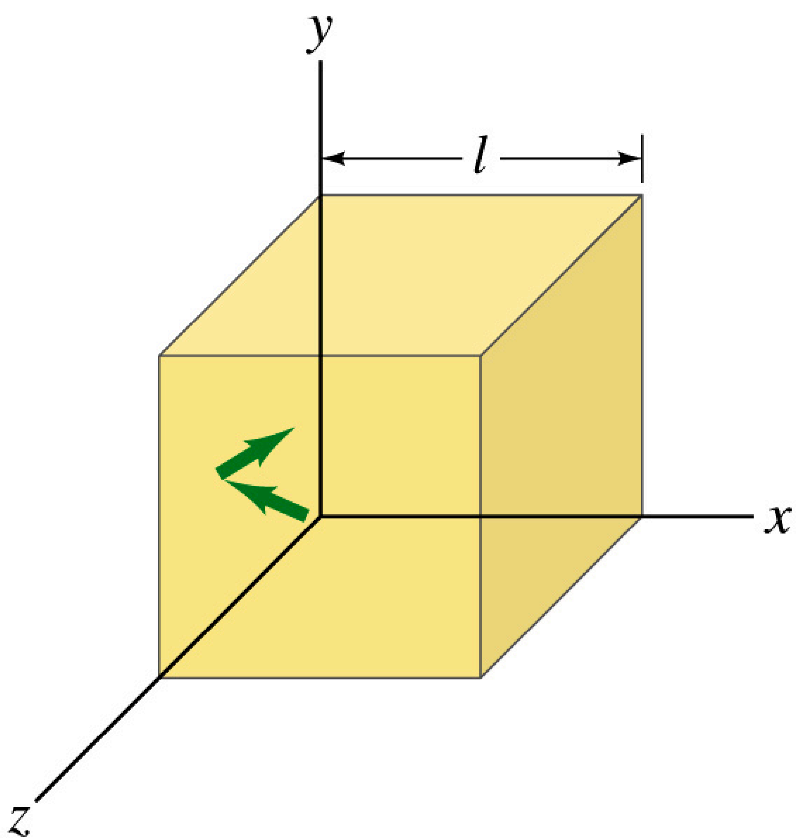
and the ideal gas law

$$pV = NkT$$

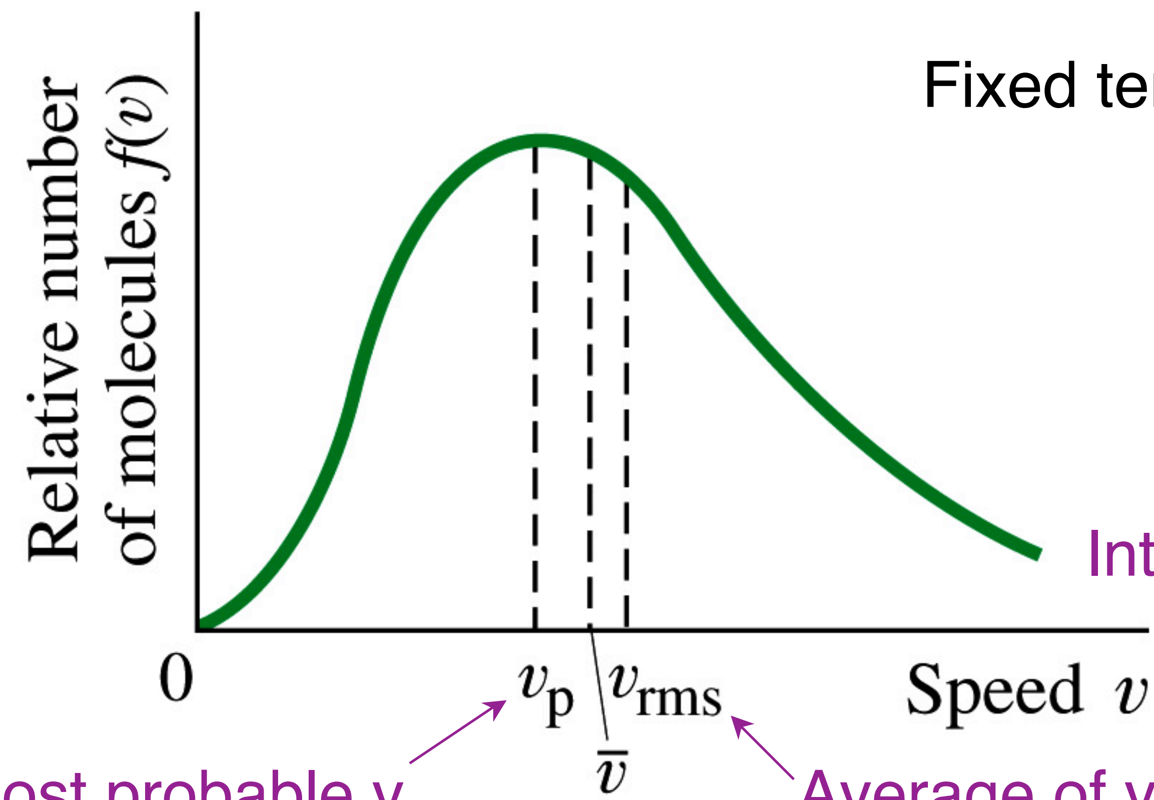
we find that

$$kT = m(v^2)_{\text{average}}/3 = (2/3)K_{\text{average}}$$

- We thus conclude that:
  - The average kinetic energy of the gas molecules is proportional to the temperature of the gas.
  - When the temperature approaches zero, the average kinetic energy approaches zero.

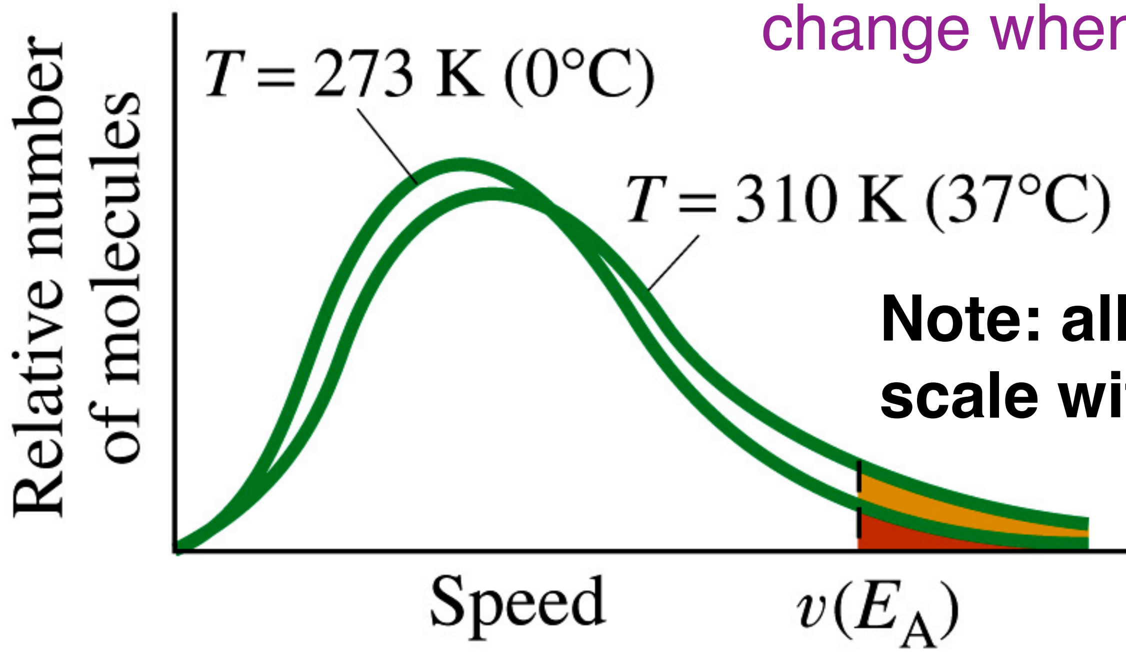


Distribution of molecular speeds. The Maxwell distribution.



Distribution of molecular speeds.
The Maxwell distribution.

Note: the integral does not change when T changes!



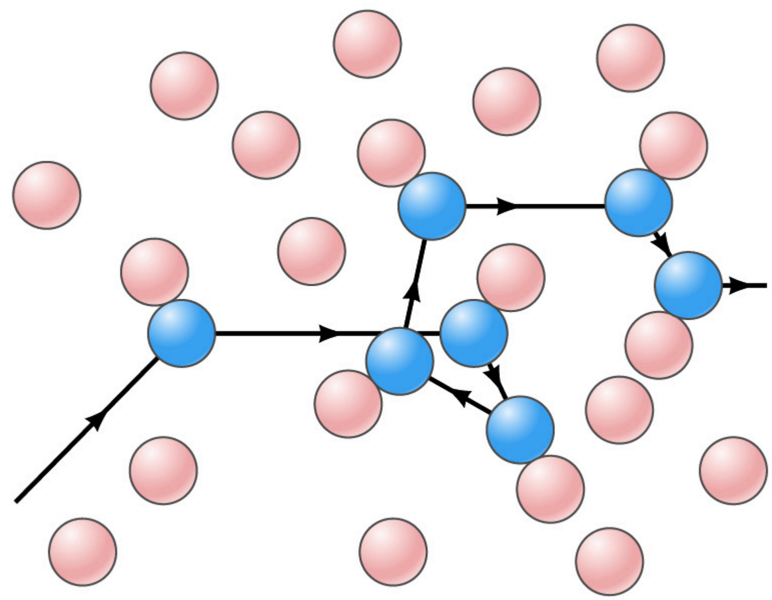
Note: all velocities scale with √ T

Increasing T increases the fraction of molecules above a certain velocity.

Frank L. H. Wolfs
Department of Physics and Astronomy, University of Rochester

Molecular speed and the mean-free path.

- The RMS velocities of individual gas molecules are large. For example for hydrogen at room temperature, the RMS velocity is 1920 m/s.
- Despite the large RMS velocity, the average diffusion velocity is much smaller and is largely determined by the mean-free path of the molecules.
- We expect that the mean-free path is inversely proportional to the cross-sectional are of the molecules and inversely proportional to the density.



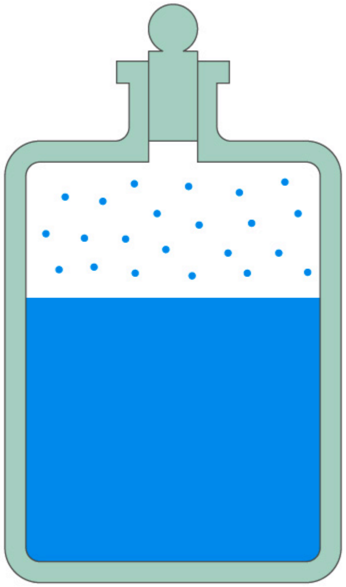
Typical values of the mean-free path are between 10^{-8} and 10^{-7} m

Molecular speed and the propagation of sound.

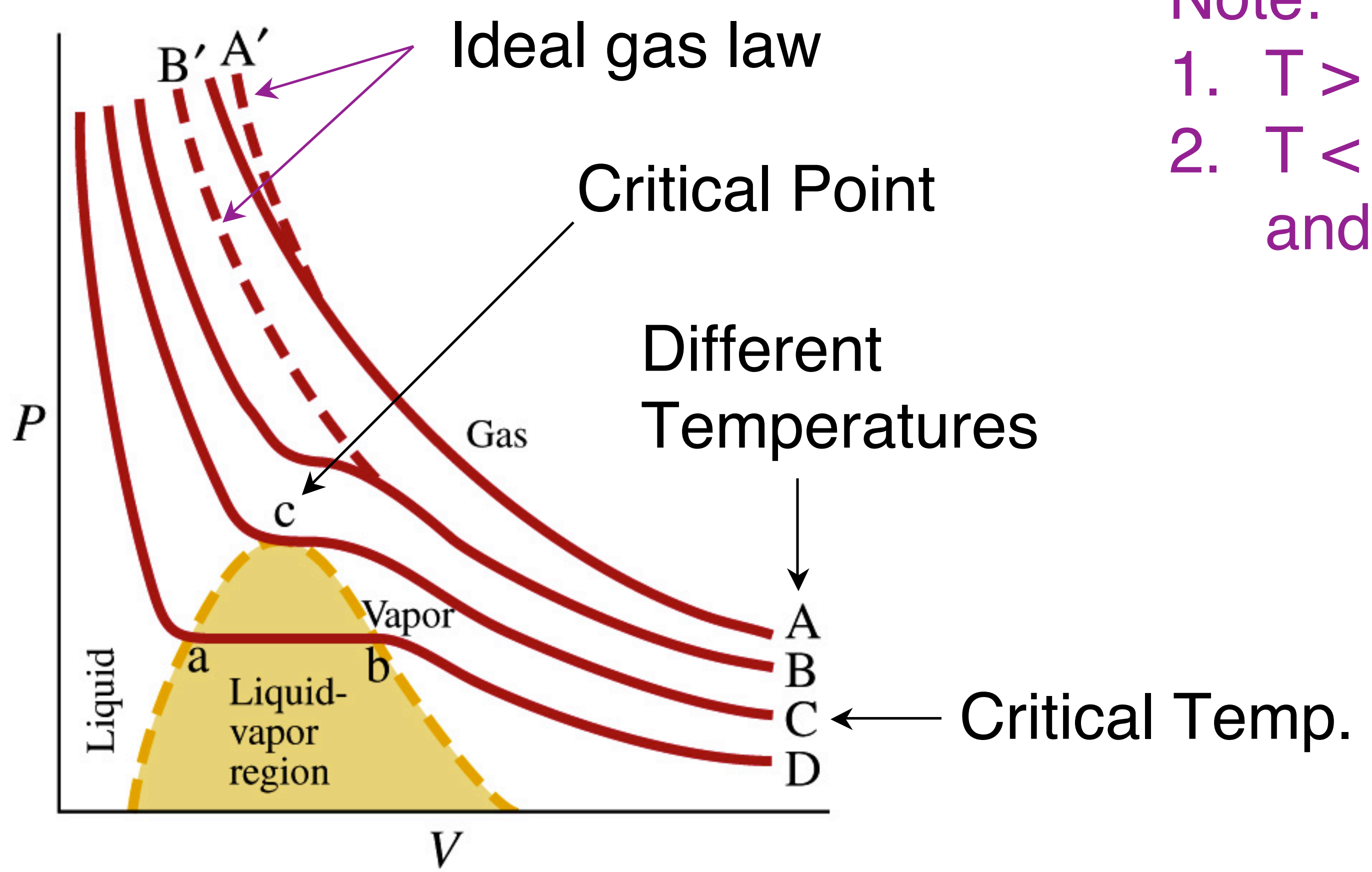
- Typical values for v_{rms}:
  - For H at 300 K, v_{rms} = 1920 m/s
  - For N at 300 K, v_{rms} = 517 m/s
- The speed of sound in these two gases is 1350 m/s for H and 350 m/s for N.
- Note: The speed of sound in a gas will always be less than v_{rms} since the sound propagates through the gas by disturbing the motion of the molecules. The disturbance is passed on from molecule to molecule by means of collisions; a sound wave can therefore never travel faster than the average speed of the molecules. Since v_{rms} increases with T, we expect v_{sound} to increase with T.

Molecular speed and evaporation.

- Evaporation: transformation from the liquid to the gas phase.
- A microscopic view of evaporation:
  - Molecules with high velocity moving close to the surface can overcome the strong attractive forces between the molecules and escape from the liquid (evaporation).
  - The average velocity of the molecules left behind in the liquid will be lowered.
  - Since the average velocity is proportional to the temperature, the temperature of the liquid is lowered when evaporation takes place.



The real equation of state. Different points of view.

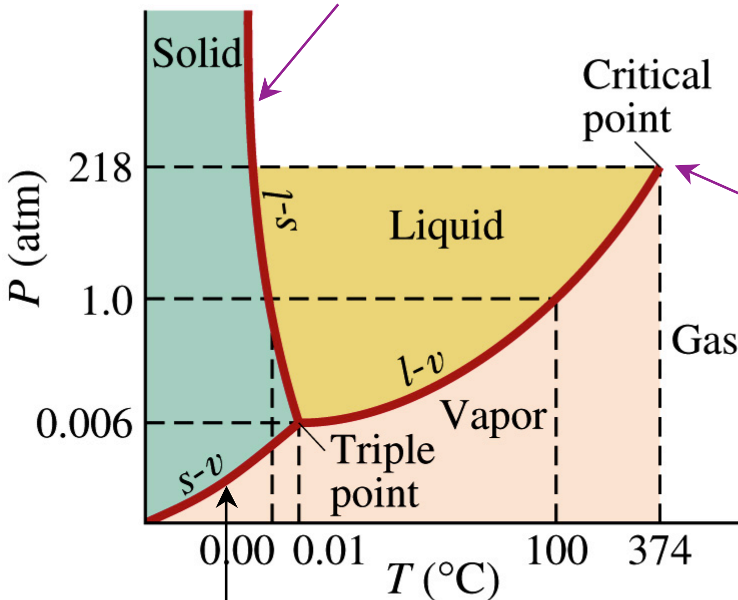


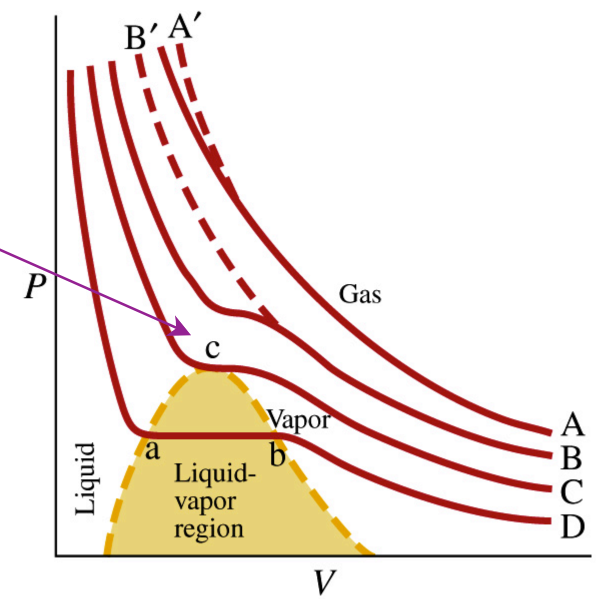
Note:

1. $T > T_c$: gas
2. $T < T_c$: liquid and/or vapor.

The real equation of state. Different points of view.

Note the curvature of the solid-liquid line.
Curvature to the left implies expansion on cooling.

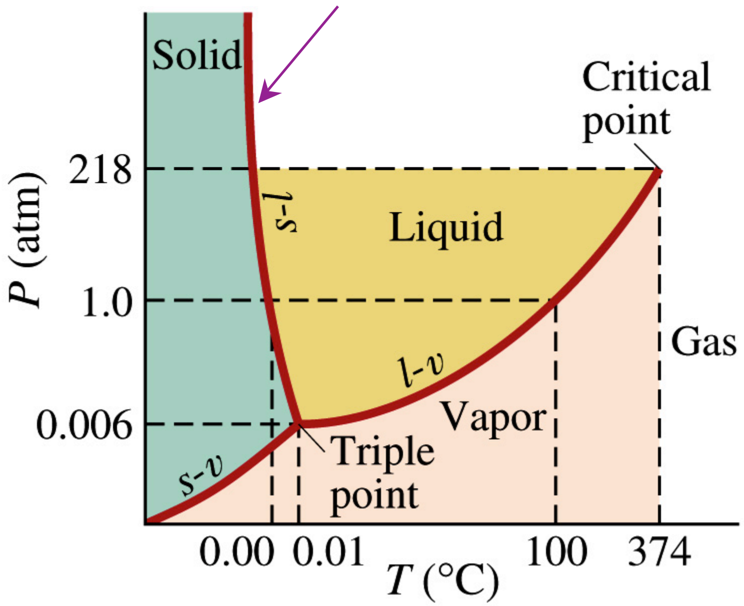




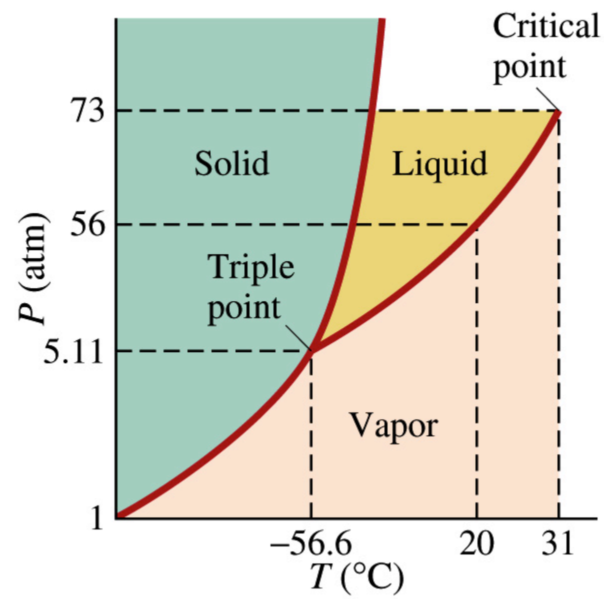
Direct change from solid to vapor.

The real equation of state. Different points of view.

Note the curvature of the solid-liquid line.
Curvature to the left implies expansion on cooling.



Water

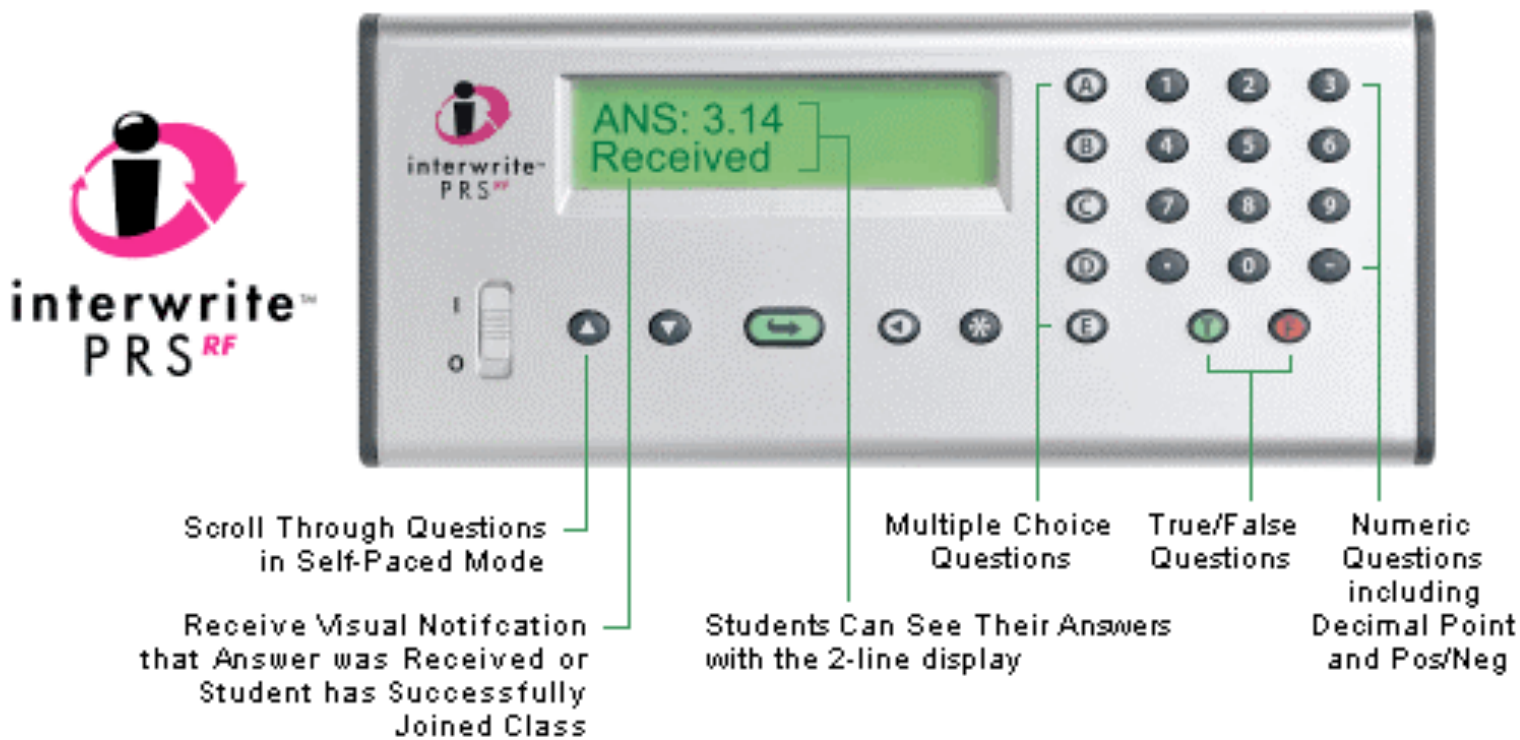


CO_2

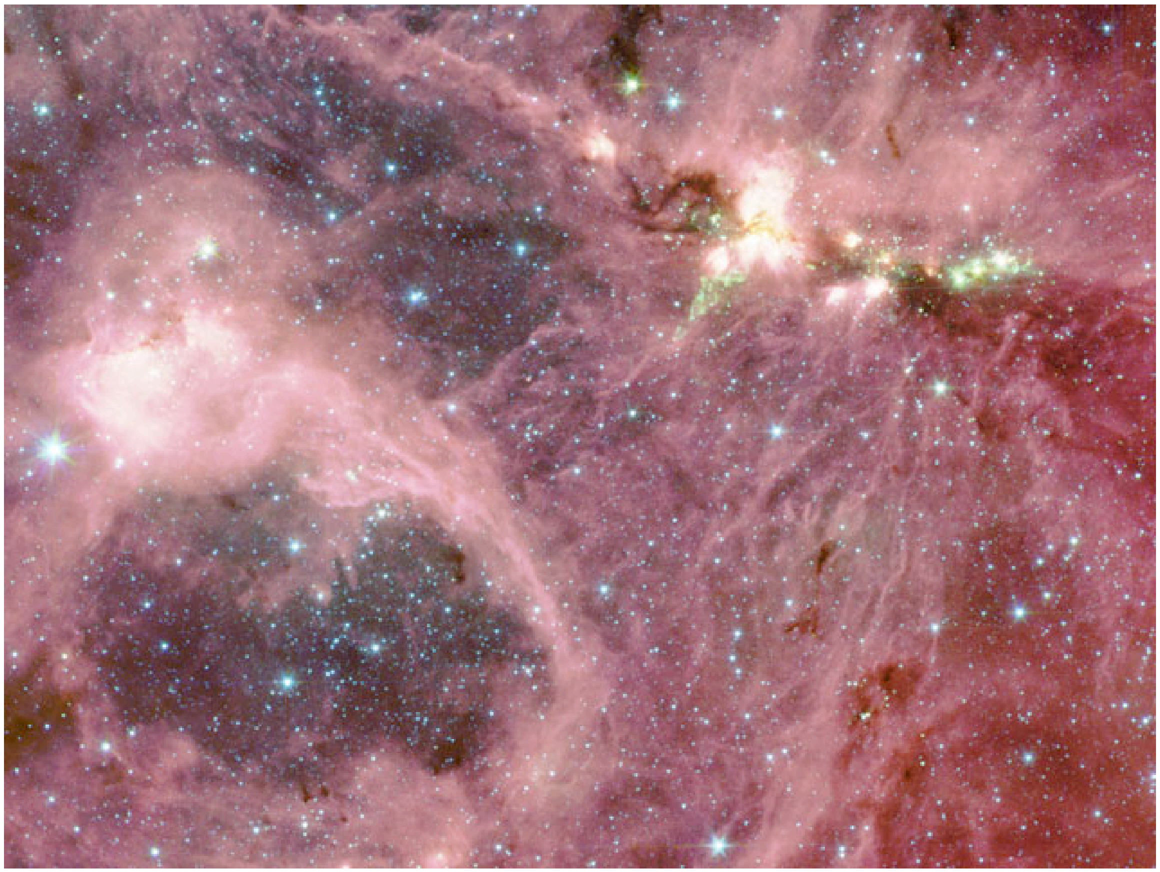
Frank L. H. Wolfs
Department of Physics and Astronomy, University of Rochester

Physics 121.
Quiz lecture 24.

- The quiz today will have 3 questions!



Done for today! Next week: The first law of thermodynamics.



Massive Star Forming Region DR21 in Infrared.
Credit: A. Marston (ESTEC/ESA) et al., JPL, Caltech, NASA