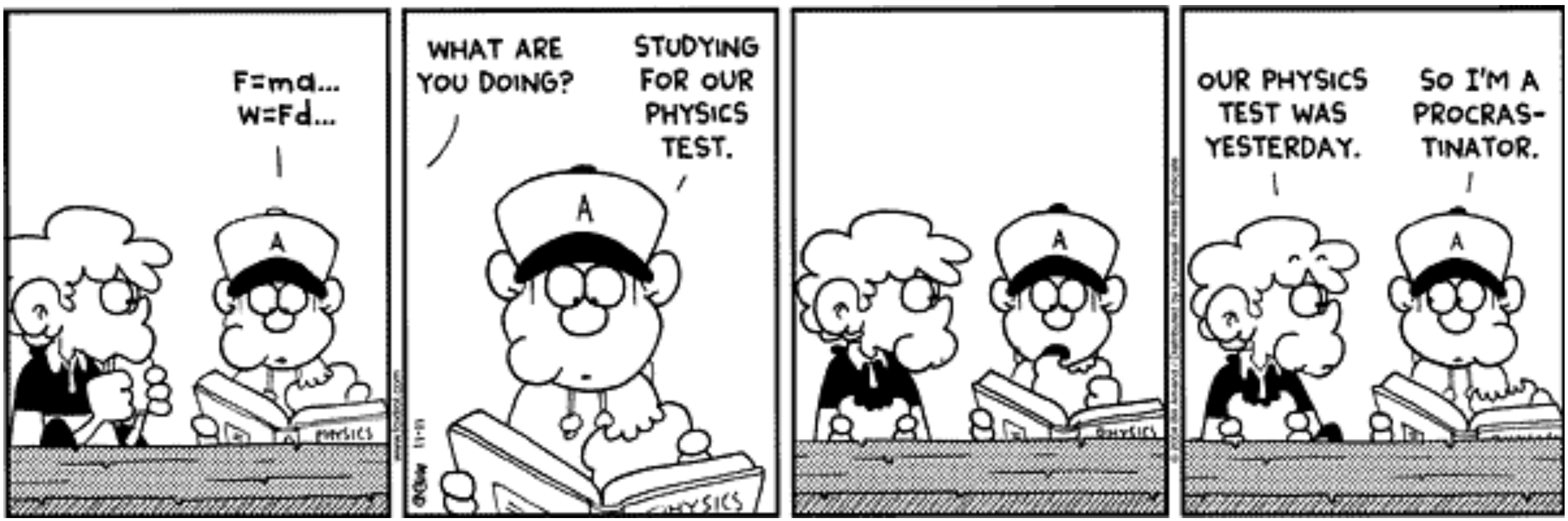
- **Theme Music:** **Duke Ellington**

  Take the A Train

- **Cartoon:** **Bill Amend**

  FoxTrot



Note:

- These Foothold slides cover the last third of the class. Since the final exam is cumulative, you should also look at the summary slides on
  - 10/3 (click on “Midterm 1” on the Schedule Page)
  - 11/7 (click on “Midterm 2” on the Schedule Page)
- Other resources include
  - clicker questions from each class (Schedule Page)
  - Midsemester exams and makeup exams (on Canvas under “Modules”)

Results by problem on each exam

	#1	#2	#3	#4	#5
Exam 1	69%	88%	82%	77%	59%
Exam 1 (MU)	43%	46%	47%	75%	45%
Exam 2	70%	84%	60%	73%	78%
Exam 2 (MU)	47%	56%	60%	58%	63%

Foothold ideas: Pressure 1

- In a gas the molecules are moving very fast in all directions. On the average the momentum cancels out.
- If you put in a wall keeping the gas on only one side, only the momentum in one direction acts on the wall (N2, N3), creating a force.
- In a non-flowing gas, the force/area is a constant, the pressure. It is proportional to the number of molecules and their mv^2.

Foothold ideas: Liquids

- In a liquid the molecules are close enough that their mutual (short ranged) attractions hold them together (e.g. H-bonding in H_2O).
- A liquid maintains its volume but changes its shape easily in response to small forces.
- The relation of p, V, and T in a liquid is <u>WAY</u> more complicated than in a gas.

Foothold ideas: Pressure 2

- A constrained fluid has an internal pressure –like an internal force at every point in all directions. (Pressure has no direction.)
- At a boundary or wall, the pressure creates a force perpendicular to the wall. $\vec{F} = p\vec{A}$
- The pressure in a fluid increases with depth. (N0, N2)

$$p = p_0 + \rho g d$$

- The pressure in a fluid is the same on any horizontal plane no matter what the shape or openings of the container. (Vessel shaped like Utah.)

Foothold ideas: Buoyancy

- ***Archimedes' principle***: When an object is immersed in a fluid (in gravity), the result of the fluid's pressure variation with depth is an upward force on the object equal to the weight of the water that would have been there if the object were not.
- As a result, an object whose density is less than that of the fluid will float, one whose density is greater than that of the fluid will sink.
- An object less dense than the fluid will float with a fraction of its volume under the fluid equal to the ratio of its density to the fluid's density.

Foothold ideas: Surface tension

- Due to the intermolecular interactions holding a liquid together, the surface of a liquid experiences a tension.
- The pull across any line in the surface of the liquid is proportional to the length of the line.

$$F_{\text{surface tension}} = \gamma L$$

Foothold ideas: Incompressible Flow

- Flow = volume / sec crossing an area.

$$Q = Av$$

- Flow in a pipe: volume in = volume out

$$A_1 v_1 = A_2 v_2$$

- Resistance to flow –
  – Drag is proportional to *v* and *L*.

$$\Delta P = ZQ$$

$$Z = 8\pi\mu \frac{L}{A^2}$$

Foothold ideas: Kinetic Energy and Work

- Newton's laws tell us how velocity changes. The Work-Energy theorem tells us how speed (independent of direction) changes.
- Kinetic energy = $\frac{1}{2}mv^2$
- Work done by a force = $\vec{F} \cdot \Delta\vec{r}$ or $F_{||}\Delta r$ (part of force || to displacement)
- Work-energy theorem: $\Delta(\frac{1}{2}mv^2) = F_{||}^{net}\Delta r$

Foothold ideas: Potential Energy

- For some forces between objects (gravity, electricity, springs) the work only depends of the change in relative position of the objects. Such forces are called <u>*conservative*</u>.
- For these forces the work done by them can be written

$$\vec{F} \cdot \Delta \vec{r}_{rel} = -\Delta U$$

- *U* is called a *potential energy* and can be considered an <u>*energy of place belonging to the two objects that can be exchanged with KE.*</u>

Foothold ideas: Potential Energy

- For some forces work only depends on the change in position. Then the work done can be written

$$\vec{F} \cdot \Delta\vec{r} = -\Delta U$$

U is called a *potential energy*.

- For gravity, $U_{gravity} = mgh$

For a spring, $U_{spring} = \frac{1}{2} kx^2$

For electric force, $U_{electric} = k_C Q_1 Q_2 / r_{12}$

Dimensions and Units of Energy

- $[1/2\ mv^2] = M\text{-}(L/T)^2 = ML^2/T^2$
- $1\ kg\text{-}m^2/s^2 = 1\ N\text{-}m = 1$ Joule
- Other units of energy are common (and will be discussed later)
  - Calorie
  - eV (electron Volt)
  - erg ($=1\ g\text{-}cm^2/s^2$)

Power

- An interesting question about work and energy is the rate at which energy is changed or work is done. This is called *power.*

$$\text{Power} = \frac{\text{Energy change}}{\text{time to make the change}}$$

$$= \frac{\Delta W}{\Delta t} = \vec{F}^{net} \cdot \frac{\Delta \vec{r}}{\Delta t} = \vec{F}^{net} \cdot \vec{v} \quad \text{(for mechanical work)}$$

- Unit of power

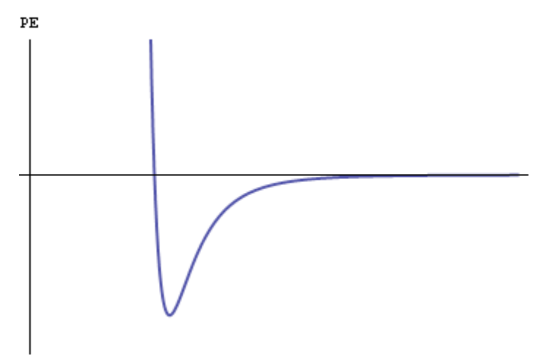
  1 Joule/sec = 1 Watt

Foothold ideas: Inter-atomic interactions

- The interaction between atoms arises from the combination of the electrical forces of its components (electrons and nuclei).
  - It can be quite complex and involve electron sharing and chemical bonds.
  - The complexity arises from the quantum character of electrons.
- Despite this complexity, a simple potential model summarizes many features of a two-atom interaction.

Foothold ideas: Inter-atomic potentials

- The interaction between neutral atoms includes an attraction at long-range that arises from the fluctuating charge distribution in each atom; the PE behaves like $1/r^6$.
- When the atoms are pressed close, they repel each other strongly; both because the +nuclei repel and because of the Pauli principle (two electrons cannot be in the same state).
- Two commonly used models are:
  - The Lennard-Jones potential (A/r^{12}-B/r^6)
  - The Morse potential (exponentials)



Foothold ideas:
Conservation of Mechanical Energy

- Mechanical energy
  - The mechanical energy of a system of objects is conserved if resistive forces can be ignored.

$$\Delta\left(KE + PE\right) = 0$$

$$KE_{initial} + PE_{initial} = KE_{final} + PE_{final}$$

- Thermal energy
  - Resistive forces transform coherent energy of motion (energy associated with a net momentum) into *thermal energy* (energy associated with internal chaotic motions and no net momentum)

Foothold ideas: Forces from PE

- For conservative forces, PE can be defined by

$$\vec{F} \cdot \Delta\vec{r} = -\Delta U$$

- If you know U, the force can be gotten from it via

$$F_{\parallel}^{type} = -\frac{\Delta U_{type}}{\Delta r} = -\frac{dU_{type}}{dr}$$

- In more than 1D need to use the *gradient*

$$\vec{F}^{type} = -\left(\frac{\partial U_{type}}{\partial x}\hat{i} + \frac{\partial U_{type}}{\partial y}\hat{j} + \frac{\partial U_{type}}{\partial z}\hat{k}\right) = -\vec{\nabla} U_{type}$$

- The force always points <u>down</u> the PE hill.

Foothold ideas: Energies between charge clusters

- Atoms and molecules are made up of charges.
- The potential energy between two charges is

$$U_{12}^{elec} = \frac{k_C Q_1 Q_2}{r_{12}}$$

No vectors!

- The potential energy between many charges is

$$U_{12\ldots N}^{elec} = \sum_{i<j=1}^{N} \frac{k_C Q_i Q_j}{r_{ij}}$$

Just add up all pairs!

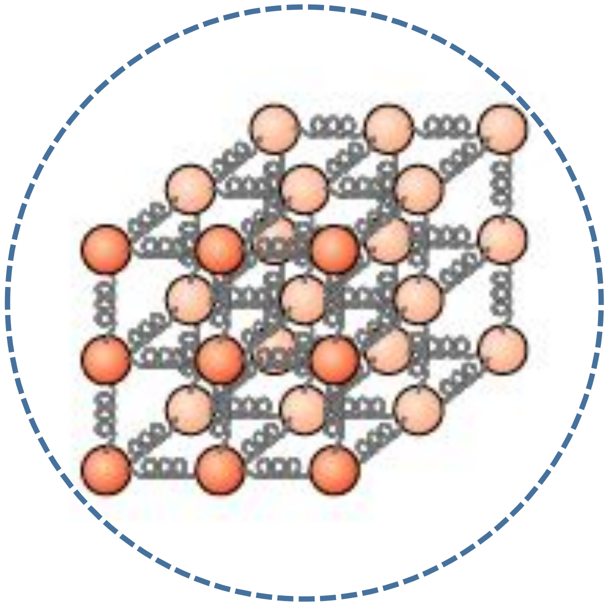
Foothold ideas: Bound states

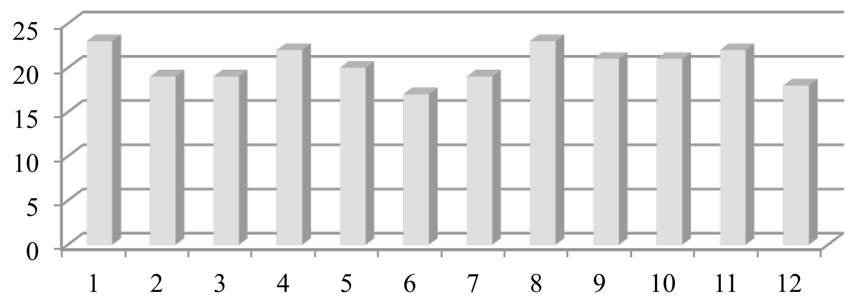
- When two objects attract, they may form a *bound state* – that is, they may stick together.
- If you have to do positive work to pull them apart in order to get to a separated state with KE = 0, then the original state was in a state with negative energy.

Temperature in any object

Object contains MANY atoms (kinetic energy) *and* interactions (potential energy)

Object A

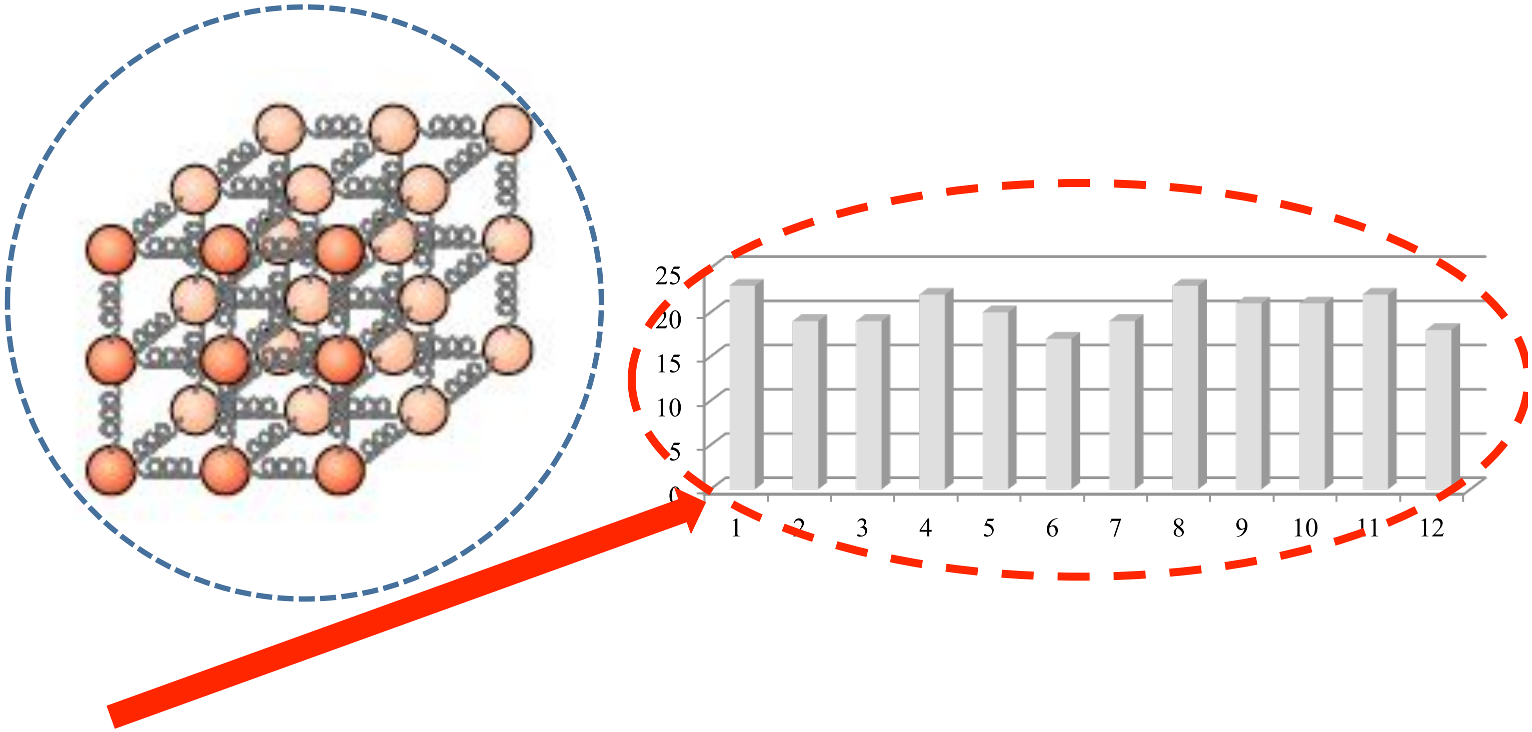




- **Temperature:** Measures the amount of energy in each atom or interaction – thermal energy is **on average** equally distributed among all these possible "bins" in which energy could reside.
- **Note: Potential energy of each bin is here defined relative to each minimum of the Potential Energy Curve.**

Thermal Energy in an object

Object A



- **Thermal energy of object A :** Measures the TOTAL energy in the whole object. Depends on temperature and the number of "bins" where energy could reside.
- Energy in each bin: ½ $k_B T$

Foothold ideas: Heat & Temperature 1

- Temperature is a measure of how hot or cold something is. (We have a natural physical sense of hot and cold.)
- When two objects are left in contact for long enough they come to the same temperature.
- When two objects of the same material but different temperatures are put together they reach an average, weighted by the fraction of the total mass.
- The mechanism responsible for the above rule is that the same thermal energy is transferred from one object to the other: Q proportional to $m\Delta T$.

Foothold ideas: Heat & Temperature 2

- When two objects of different materials and different temperatures are put together they come to a common temperature, but it is not obtained by the simple rule.
- Each object translates thermal energy into temperature in its own way. This is specified by a density-like quantity, *c*, the specific heat.
- The heat capacity of an object is $C = mc$.
- When two objects of different material and different temperatures are put together they reach an average, weighted by the fraction of the total heat capacity.
- When heat is absorbed or emitted by an object $Q = \pm mc\Delta T$