- **<u>Theme Music:</u> Duke Ellington**

  Take the A Train

- **<u>Cartoon:</u> Lynn Johnston**

  For Better or for Worse

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
  - 10/9 (click on “Midterm 1” on the Schedule Page)
  - 11/13 (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	91%	73%	58%	51%	66%
Exam 1 (MU)	47%	37%	48%	54%	66%
Exam 2	72%	79%	37%	58%	74%
Exam 2 (MU)	62%	50%	39%	59%	58%

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

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

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

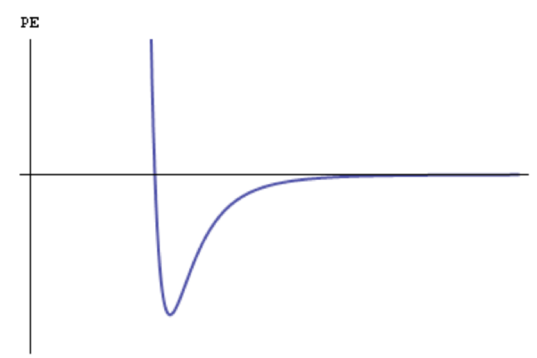
1 Joule/sec = 1 Watt

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.

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 $Q = \pm mc\Delta T$

Foothold ideas: Heat flow

- Objects in contact at different temperatures will tend to exchange energies so that the hotter cools down, the cooler warms up, until they reach the same temperature. (0^{th} Law)
- The rates at which thermal energy leaves or enters an object is a property of the material of which the object is made and its surface.
- When we touch an object, we measure the rate of flow of thermal energy – not temperature.

Foothold ideas: Kinds of internal energy

- *Thermal Energy* – Energy of random motion of the atoms and molecules of an object. Can be kinetic or potential (for solids and liquids).
- *Chemical Energy* – Internal kinetic and potential energy of electrons inside an atom.

Foothold ideas: Mechanical Energy & the 1st Law of Thermodynamics

Coherent energy
Kinetic and potential

Internal energy: random motion of small stuff we don't want to talk about

$$E = KE + PE + U_{\text{int}}$$

$$\Delta E = \Delta(KE) + \Delta(PE) + \Delta U_{\text{int}}$$

Energy of System
(not moving coherently)

Thermal energy
Entering system

Work done
on system

$$\Delta U_{\text{int}} = Q + W$$