Basic Physics, Part II

Work, Energy, and Power

Energy: the capacity to do work

- This notion makes sense even in a colloquial context:
  - hard to get work done when you're wiped out (low on energy)
  - work makes you tired: you've used up energy
- But we can make this definition of energy much more precise by specifying exactly what we mean by *work*

Work: more than just unpleasant tasks

- In physics, the definition of work is the application of a *force through a distance*

$$W = F \cdot d$$

- W is the *work* done
- F is the *force* applied
- d is the *distance* through which the force acts
- Only the force that acts in the direction of motion counts towards work

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Units of Energy

- Force is a mass times an acceleration
  - mass has units of kilograms
  - acceleration is m/s^2
  - force is then $kg \cdot m/s^2$, which we call Newtons (N)
- Work is a force times a distance
  - units are then $(kg \cdot m/s^2) \cdot m = kg \cdot m^2/s^2 = N \cdot m$ = Joules (J)
  - One joule is one Newton of force acting through one meter
  - Imperial units of force and distance are pounds and feet, so unit of energy is foot-pound, which equals 1.36 J
- Energy has the same units as work: Joules

A note on arithmetic of units

- You should carry units in your calculations and multiply and divide them as if they were numbers
- Example: the force of air drag is given by:

  $F_{drag} = \frac{1}{2} c_D \rho A v^2$

  - c_D is a dimensionless drag coefficient
  - ρ is the density of air, 1.3 kg/m^3
  - A is the cross-sectional area of the body in m^2
  - v is the velocity in m/s

  units: $(\mathrm{kg/m^3})\cdot(\mathrm{m^2})\cdot(\mathrm{m/s})^2 = (\mathrm{kg\cdot m^2/m^3})\cdot(\mathrm{m^2/s^2}) = \dfrac{\mathrm{kg\cdot m^2\cdot m^2}}{\mathrm{m^3\cdot s^2}}$

  $$= \frac{\mathrm{kg\cdot m^4}}{\mathrm{m^3\cdot s^2}} = \mathrm{kg\cdot m/s^2} = \mathrm{Newtons}$$

Kinetic Energy

- Kinetic Energy: the energy of motion
- Moving things carry energy in the amount:

  $K.E. = \frac{1}{2} m v^2$
- Note the v^2 dependence—this is why:
  - a car at 60 mph is 4 times more dangerous than a car at 30 mph
  - hurricane-force winds at 100 mph are much more destructive (4 times) than 50 mph gale-force winds
  - a bullet shot from a gun is at least 100 times as destructive as a *thrown* bullet, even if you can throw it a tenth as fast as you could shoot it

Numerical examples of kinetic energy

- A baseball (mass is 0.145 kg = 145 g) moving at 30 m/s (67 mph) has kinetic energy:

  K.E. = $\frac{1}{2} \times (0.145\ \mathrm{kg}) \times (30\ \mathrm{m/s})^2$

  $= 65.25\ \mathrm{kg\cdot m^2/s^2} \approx 65$ J
- A quarter (mass = 0.00567 kg = 5.67 g) flipped about four feet into the air has a speed on reaching your hand of about 5 m/s. The kinetic energy is:

  K.E. = $\frac{1}{2} \times (0.00567\ \mathrm{kg}) \times (5\ \mathrm{m/s})^2$

  $= 0.07\ \mathrm{kg\cdot m^2/s^2} = 0.07$ J

More numerical examples

- A 1500 kg car moves down the freeway at 30 m/s (67 mph)

  K.E. = $\frac{1}{2} \times (1500\ \mathrm{kg}) \times (30\ \mathrm{m/s})^2$

  $= 675{,}000\ \mathrm{kg\cdot m^2/s^2} = 675$ kJ
- A 2 kg (~4.4 lb) fish jumps out of the water with a speed of 1 m/s (2.2 mph)

  K.E. = $\frac{1}{2} \times (2\ \mathrm{kg}) \times (1\ \mathrm{m/s})^2$

  $= 1\ \mathrm{kg\cdot m^2/s^2} = 1$ J

Gravitational Potential Energy

- It takes *work* to lift a mass against the pull (force) of gravity
- The force of gravity is $m \cdot g$, where m is the mass, and g is the gravitational acceleration

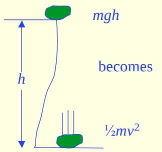
  $F = mg$ (note similarity to $F = ma$)
  - $g = 9.8\ \text{m/s}^2$ on the surface of the earth
  - $g \approx 10\ \text{m/s}^2$ works well enough for this class
- Lifting a height h against the gravitational force requires an energy input (work) of:

  $\Delta E = W = F \cdot h = mgh$
- Rolling a boulder up a hill and perching it on the edge of a cliff gives it gravitational *potential* energy that can be later released when the roadrunner is down below.

First Example of Energy Exchange

- When the boulder falls off the cliff, it picks up speed, and therefore gains kinetic energy
- Where does this energy come from??

  ⇒ from the *gravitational potential energy*
- The higher the cliff, the more kinetic energy the boulder will have when it reaches the ground



Energy is conserved, so
$\frac{1}{2}mv^2 = mgh$

Can even figure out v, since $v^2 = 2gh$

Examples of Gravitational Potential Energy

- How much gravitational potential energy does a 70 kg high-diver have on the 10 meter platform?

  $mgh = (70\ \text{kg})\times(10\ \text{m/s}^2)\times(10\ \text{m})$

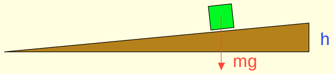
  $= 7{,}000\ \text{kg}\cdot\text{m}^2/\text{s}^2 = 7\ \text{kJ}$
- How massive would a book have to be to have a potential energy of 40 J sitting on a shelf two meters off the floor?

  $mgh = m\times(10\ \text{m/s}^2)\times(2\ \text{m}) = 40\ \text{J}$

  so m must be 2 kg

Ramps Make Life Easy

- To get the same amount of work done, you can either:
  - apply a LARGE force over a small distance
  - OR apply a small force over a large distance
  - as long as $W = F \cdot d$ is the same



- Ramp with 10:1 ratio, for instance, requires one tenth the force to push a crate up it (disregarding friction) as compared to lifting it straight up
  - total work done to raise crate is still the same: mgh
  - but if the work is performed over a longer distance, F is smaller: $mg/10$

The Energy of Heat

- Hot things have more energy than their cold counterparts
- Heat is really just kinetic energy on microscopic scales: the vibration or otherwise fast motion of individual atoms/molecules
    - Even though it's kinetic energy, it's hard to derive the same useful work out of it because the motions are *random*
- Heat is frequently quantified by calories (or Btu)
    - One calorie (4.184 J) raises one gram of H_2O 1ºC
    - One Calorie (4184 J) raises one kilogram of H_2O 1ºC
    - One Btu (1055 J) raises one pound of H_2O 1ºF

Energy of Heat, continued

- Food Calories are with the "big" C, or kilocalories (kcal)
- Since water has a density of one gram per cubic centimeter, 1 cal heats 1 c.c. of water 1ºC, and likewise, 1 kcal (Calorie) heats one liter of water 1ºC
    - these are useful numbers to hang onto
- Example: to heat a 2-liter bottle of Coke from the 5ºC refrigerator temperature to 20ºC room temperature requires 30 Calories, or 122.5 kJ

Heat Capacity

- Different materials have different *capacities* for heat
    - Add the same energy to different materials, and you'll get different temperature rises
    - Quantified as heat capacity
    - Water is exceptional, with 4,184 J/kg/ºC
    - Most materials are about 1,000 J/kg/ºC (including wood, air, metals)
- Example: to add 10ºC to a room 3 meters on a side (cubic), how much energy do we need?

    air density is 1.3 kg/m^3, and we have 27 m^3, so 35 kg of air; and we need 1000 J per kg per ºC, so we end up needing 350,000 J (= 83.6 Cal)

Chemical Energy

- Electrostatic energy (associated with charged particles, like electrons) is stored in the chemical bonds of substances.
- Rearranging these bonds can release energy (some reactions *require* energy to be put in)
- Typical numbers are 100–200 kJ per mole
    - a mole is 6.022×10^{23} molecules/particles
    - works out to typical numbers like several thousand Joules per gram, or a few Calories per gram (remember, 1 Cal = 1 kcal = 4184 J)

Chemical Energy Examples

- Burning a wooden match releases about one Btu, or 1055 Joules (a match is about 0.3 grams), so this is >3,000 J/g, nearly 1 Cal/g
- Burning coal releases about 20 kJ per gram of chemical energy, or roughly 5 Cal/g
- Burning gasoline yields about 39 kJ per gram, or just over 9 Cal/g

Power

- Power is simply energy exchanged per unit time, or how fast you get work done (Watts = Joules/sec)
- One horsepower = 745 W
- Perform 100 J of work in 1 s, and call it 100 W
- Run upstairs, raising your 70 kg (700 N) mass 3 m (2,100 J) in 3 seconds → 700 W output!
- Shuttle puts out a few GW (gigawatts, or 10^9 W) of power!

Power Examples

- How much power does it take to lift 10 kg up 2 meters in 2 seconds?

  mgh = (10 kg)×(10 m/s^2)×(2 m) = 200J

  200 J in 2 seconds → 100 Watts
- If you want to heat the 3 m cubic room by 10ºC with a 1000 W space heater, how long will it take?

  We know from before that the room needs to have 360,000 J added to it, so at 1000 W = 1000 J/s this will take 360 seconds, or six minutes.

  But: the walls need to be warmed up too, so it will actually take longer (and depends on quality of insulation, etc.)

Announcements/Assignments

- Next up:
  - flow of energy and human energy/exercise
  - a simple model for molecules/lattices
  - electrons, charge, current, electric fields
- Assignments:
  - Transmitters start counting for participation credit Tuesday 4/11
  - HW1: Chapter 1 in Bloomfield: 1.E.4, 1.E.7, 1.E.8, 1.E.20, 1.E.25, 1.E.34, 1.P.1, 1.P.8, 1.P.9, 1.P.10, 1.P.14, 1.P.16, 1.P.18, 1.P.22; Chapter 2: 2.E.28, 2.P.10, 2.P.11
    - E → Exercise; P → Problem
    - due Thursday 4/13 in class (or in box outside 336 SERF by 3:30PM Thursday)
  - First Q/O due Friday, 4/14 by 6PM via WebCT
  - read chapter 2: pp. 54–59, 61–62, 71–72; chapter 7: pp. 206–207