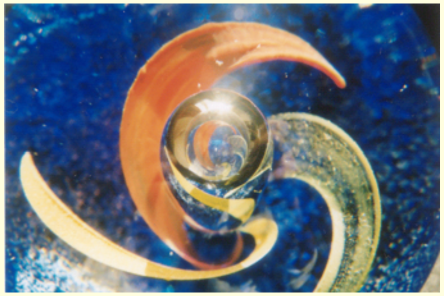


The Flow of Energy

Where it comes from; where it goes

Energy as a tool in physics

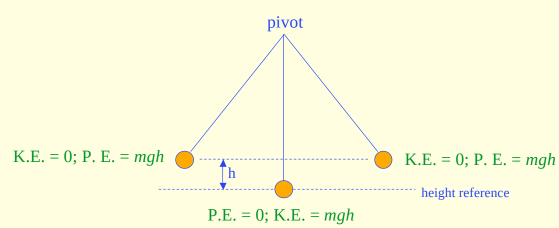
- Energy is a very abstract notion, but it is a very useful and quantifiable notion
- We use the conservation of energy to predict behavior
  - by setting $E = mgh + \frac{1}{2}mv^2$ = constant we can elucidate the value of the velocity at any height:
    $v^2 = 2g\times$(height fallen from rest)
  - We rely on the fact that energy is not created out of nowhere
- Where did the energy we see around us come from?
  - most of what we use derives from the sun
  - some derives from other, exploded stars (nuclear fission)
  - ultimately, all of it was donated in the Big Bang
    - but surprisingly, the net energy of the universe can be (and looks to be) zero!

Energy is Conserved

- Conservation of Energy is different from Energy Conservation, the latter being about using energy wisely
- Conservation of Energy means energy is neither created nor destroyed. The total amount of energy in the Universe is constant!!
- Don't we *create* energy at a power plant?
  - No, we simply *transform* energy at our power plants
- Doesn't the sun *create* energy?
  - Nope—it *exchanges* mass for energy

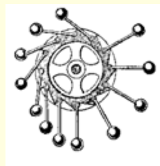
Energy Exchange

- Though the total energy of a system is constant, the *form* of the energy can change
- A simple example is that of a pendulum, in which a continual exchange goes on between kinetic and potential energy



Perpetual Motion

- Why won't the pendulum swing forever?
- It's impossible to design a system free of energy paths
- The pendulum slows down by several mechanisms
  - Friction at the contact point: requires force to oppose; force acts through distance → work is done
  - Air resistance: must push through air with a force (through a distance) → work is done
  - Gets some air swirling: puts kinetic energy into air (not really fair to separate these last two)
- Perpetual motion means *no loss of energy*
  - solar system orbits come very close



Some Energy Chains:

- A toilet bowl with some gravitational potential energy is dropped
- potential energy turns into kinetic energy
- kinetic energy of the toilet bowl goes into:
  - ripping the toilet bowl apart (chemical: breaking bonds)
  - sending the pieces flying (kinetic)
  - into sound
  - into heating the ground and pieces through friction as the pieces slide to a stop
- In the end, the local environment is slightly warmer

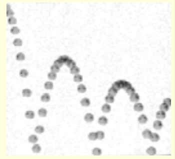
How Much Warmer?

- A 20 kg toilet bowl held 1 meter off the ground has 200 J of gravitetional potential energy
  - mgh = (20 kg)(10 m/s^2)(1 m) = 200 kg·m^2/s^2 = 200 J
- A typical heat capacity is 1000 J/kg/°C (a property of the material)
- So 200 J can heat 0.2 kg of material by 1°C or 1 kg by 0.2°C or 20 kg by 0.01°C
  - heat capacity follows intuitive logic:
    - to get same ΔT, need more energy or less mass
    - given fixed energy input, get smaller ΔT for larger mass
    - for a given mass, get larger ΔT for more energy input
- So how much mass is effectively involved?
  - initially not much (just contact surfaces): so hot at first
  - but heat diffuses into surrounding bulk: cools down
  - so answer is ill-defined: depends on *when*
- But on the whole, the temperature rise is hardly noticeable

Gasoline Example

- Put gas in your car
- Combust gas, turning chemical energy into kinetic energy of the explosion (motion of gas particles)
- Transfer kinetic energy of gas to piston to crankshaft to drive shaft to wheel to car as a whole
- That which doesn't go into kinetic energy of the car goes into heating the engine block (and radiator water and surrounding air), and friction of transmission system (heat)
- Much of energy goes into stirring the air (ends up as heat)
- Apply the brakes and convert kinetic energy into heat
- It all ends up as waste heat, ultimately

Bouncing Ball



- Superball has gravitational potential energy
- Drop the ball and this becomes kinetic energy
- Ball hits ground and compresses (force times distance), storing energy in the spring
- Ball releases this mechanically stored energy and it goes back into kinetic form (bounces up)
- Inefficiencies in “spring” end up heating the ball and the floor, and stirring the air a bit
- In the end, all is heat

Why don’t we get hotter and hotter

- If all these processes end up as heat, why aren’t we continually getting hotter?
- If earth retained all its heat, we *would* get hotter
- All of earth’s heat is *radiated* away as infrared light
  - hotter things radiate more heat
- If we dump more power, the temperature goes up, the radiated power increases dramatically
  - comes to equilibrium: power dumped = power radiated
  - stable against perturbation: T tracks power budget

Another Piece of the Energy Zoo: Light

- The power given off of a surface in the form of light is proportional to the *fourth power* of that surface’s temperature!

  $P = A\sigma T^4$ in Watts
  - the constant, σ, is numerically 5.67×10^{-8} W/ºK^4/m^2
  - easy to remember constant: 5678
  - A is surface area of hot thing, in square meters
  - temperature must be in Kelvin:
    - ºK = ºC + 273
    - ºC = (5/9)×(ºF –32)
- Example: radiation from your body:

  $(1\text{ m}^2)(5.67\times10^{-8})\times(310)^4 = 523$ Watts

  (if naked in the cold of space: don’t let this happen to you!)

Radiant Energy, continued

- Example: The sun is 5800ºK on its surface, so:

  $P/A = \sigma T^4 = (5.67\times10^{-8})\times(5800)^4 = 6.4\times10^7$ W/m^2

  Summing over entire surface area of sun gives 3.9×10^{26} W
- Compare to total capacity of human energy “production” on earth: 3.3×10^{12} W
  - Single power plant is typically 0.5–1.0 GW (10^9 W)
- In earthly situations, radiated power out is partially *balanced* by radiated power in from other sources
  - Not 523 W/m^2 in 70ºF room, more like 100 W/m^2
    - goes like $\sigma T_h^4 - \sigma T_c^4$

Rough numbers

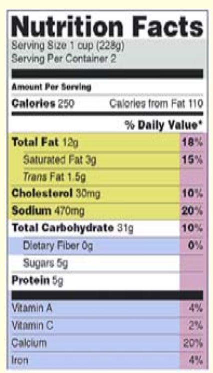
- How much power does the earth radiate?
- $P/A = \sigma T^4$ for T = 288ºK = 15ºC is 390 W/m²
- Summed over entire surface area ($4\pi R^2$, where R = 6,378,000 meters) is 2.0×10^{17} W
  - For reference, global "production" is 3×10^{12} W
- Solar radiation incident on earth is 1.8×10^{17} W
  - just solar luminosity of 3.9×10^{26} W divided by geometrical fraction that points at earth
- Amazing coincidence of numbers! (or is it…)

No Energy for Free

- No matter what, you can't create energy out of nothing: it has to come from somewhere
- We can *transform* energy from one form to another; we can *store* energy, we can *utilize* energy being conveyed from natural sources
- The net energy of the entire Universe is constant
- The best we can do is scrape up some useful crumbs

Energy and Calories

- A calorie is a unit of energy (1 cal is the amount of energy required to raise the temperature of 1 cc of water 1˚C.)
  - 1 cal = 4.184 J
- Food Calories are measured in kcal (1 Cal = 1000 cal)
  - 1 Cal = 4184 J
- 250 Calories is enough energy to raise 250 liters (about 66 gallons) of water 1˚C.



Nutrition Facts
Serving Size 1 cup (228g)
Serving Per Container 2

Amount Per Serving	
Calories 250	Calories from Fat 110
	% Daily Value*
Total Fat 12g	18%
Saturated Fat 3g	15%
Trans Fat 1.5g	
Cholesterol 30mg	10%
Sodium 470mg	20%
Total Carbohydrate 31g	10%
Dietary Fiber 0g	0%
Sugars 5g	
Protein 5g	
Vitamin A	4%
Vitamin C	2%
Calcium	20%
Iron	4%

Human Energy Requirements

- 1,500 Calories per day just to be a couch-potato
  - 6,280,000 J
- Average human power consumption is then:
  - 6.28 MJ / 86,400 seconds ≈ 75 W
  - We're like light bulbs, constantly putting out heat
- Need more like 2,000 Cal for active lifestyle
  - 100 W of power

Energy from Food

Nutrition Facts
Serving Size 2/3 cup (52g)
Servings Per Container: 6

Amount Per Serving	
Calories 180	Calories from Fat 60
	% DailyValue*
Total Fat 7g	10%
Saturated Fat 1g	4%
Cholesterol 0mg	0%
Sodium 60mg	3%
Potassium 230mg	7%
Total Carbohydrate 28g	9%
Dietary Fiber 7g	27%
Sugars 12g	
Protein 10g (5g from soy)	
Vitamin A 0% •	Vitamin C 2%
Calcium 6% •	Iron 15%

- Energy from fat, carbohydrates, protein
  - 9 Calories per gram for fat
  - 7 Calories per gram for alcohol
  - 4 Calories per gram for carbohydrate
    - Fiber part doesn't count
  - 4 Calories per gram for protein
- Calculate 63 fat, 84 CH, 40 protein Cals
  - total is 187 Calories (180 is in the ballpark)
- 1 Calorie (kilo-calorie) is 4,187 J
  - 180 Cal = 753 kJ
  - set equal to *mgh*→ climb 1100 m vertically, assuming perfect efficiency

Not So Fast…

- Human body isn't 100% efficient: more like 25%
  - To put out 100 J of mechanical work, must eat 400 J
  - 180 Calorie candy bar only gets us 275 m, not 1100 m
- Maximum sustained power output (rowing, cycling) is about 150-200 W (for 70 kg person)
  - Consuming 600-800 W total, mostly as wasted heat
  - For 30 minutes → 800 J/s ×1800 s = 1.44 MJ = 343 Cal
- Can burst 700 W to 1000 W for < 30 sec
  - put out a full horsepower momentarily!

Most impressive display of human power

- The Gossamer Albatross crossed the English Channel in 1979, powered by Bryan Allen
  - Flight took 49 minutes, wiped Bryan out!
  - Sustained power out ~250 W

Human Energy Requirements Summarized

- We need chemical energy from food to run
  - Ultimate source is sun, long chain of events to twinkies
  - Constantly burn energy at rate of 75-100W
  - We spend energy at about 25% efficiency
  - Maximum sustained power is 150-200 W
    - actually burn 4 times this due to inefficiencies

Air Resistance

- We're always "neglecting air resistance" in physics
  - Can be difficult to deal with
- Affects projectile motion
  - Friction force opposes velocity through medium
  - Imposes horizontal force, additional vertical forces
  - Terminal velocity for falling objects
- Dominant energy drain on cars, bicyclists, planes

Drag Force Quantified

- With a cross sectional area, *A* (in m²), coefficient of drag of 1.0 (most objects), sea-level density of air, and velocity, *v* (m/s), the drag force is:

$$F_{drag} = ½ c_D \cdot \rho \cdot A \cdot v^2 \text{ Newtons}$$

  - c_D is drag coefficient: ~1.0 for most things, 0.35 for car
  - ρ is density of medium: 1.3 kg/m³ for air, 1000 kg/m³ water
  - typical object in air is then $F_{drag} \approx 0.65 \cdot A \cdot v^2$
- Example: Bicycling at 10 m/s (22 m.p.h.), with projected area of 0.5 m² exerts 32.5 Newtons
  - requires $F \cdot v$ of *power* → 325 Watts to maintain speed

"Free" Fall

- Terminal velocity reached when $F_{drag} = F_{grav}$ (= mg)
- For 75 kg person subtending 0.5 m²,

$$v_{term} \approx 50 \text{ m/s, or 110 m.p.h.}$$

which is reached in about 5 seconds, over 125 m of fall

  - actually takes slightly longer, because acceleration is reduced from the nominal 10 m/s² as you begin to encounter drag
- Free fall only lasts a few seconds, even for skydivers

Announcements/Assignments

- Next up:
  - a simple model for molecules/lattices
  - electrons, charge, current, electric fields
- Assignments:
  - read chapter 7, pp. 212–214, 225–228
  - read chapter 3, 83–87; chapter 9 265–269, 278–279
  - HW1: 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.10 (in Newtons), 1.P.14, 1.P.16, 1.P.18, 1.P.22, 2.E.28, 2.P.10, 2.P.11: due 4/13
  - First Q/O due Friday, 4/14 by 6PM via WebCT