Many
Slides
Are
From
Prof.
Tom
Murphy
(with
Permission)
Thank
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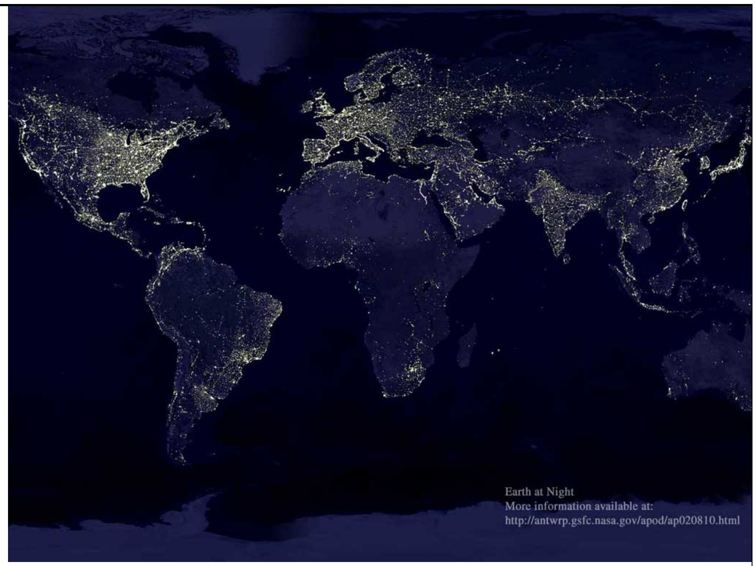


Energy

Course Preview: the Big Picture

- We use *a heck of a lot* of energy
  - primitive society uses < 100 W of power per person
  - our modern society burns 10,000 W per person
  - surely not in our homes! Where is this going on?
- Energy availability has enabled us to focus on higher-level issues as a society
  - art
  - science
  - home shopping network

- Long ago, almost all of our energy came from food (delivering muscle power), and almost all our energy went into securing food for ourselves
- Enter the work animal, supplementing our muscle power and enabling larger-scale agriculture
- Next burn wood to run boilers, trains
- 150 years ago, muscular effort and firewood provided *most* of our energy—and today this is less than 1% of the story
- Today, much more energy *goes into* growing/ harvesting food than *comes out of* food!
- Today in US 86% of our energy comes from fossil fuels (oil,natural gas, coal)

Fuzzy on the concept of energy?

- Don’t worry—we’ll cover that.

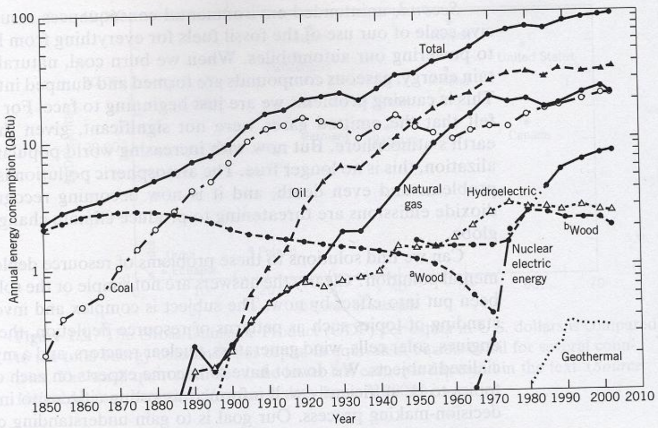
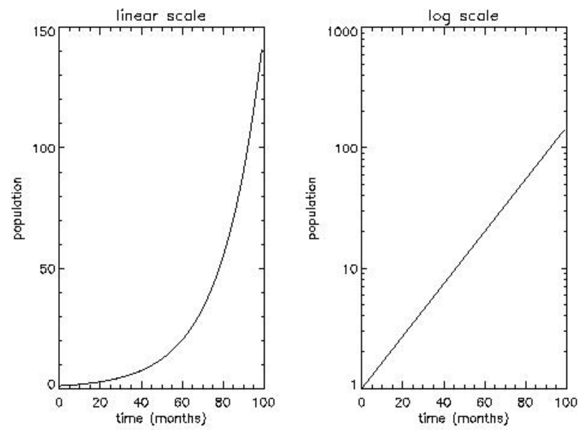


Figure 1.1 Various forms of energy consumed in the United States since 1850. This type of graph is called a semilogarithmic plot, an explanation of the scales is given in the Appendix. *Sources: Historical Statistics of the United States, Colonial Times to 1970*, U.S. Department of Commerce. Bureau of the Census, 1975; U.S. Energy Information Administration, *Annual Energy Review*, 2003. (a) The wood data set from 1850 to 1970 is from the first source. (b) The wood data set from 1950 to 2003 is from the second source; it includes wood, black liquor (a byproduct of the wood-based paper production process), and wood waste.

A note on graphs: log vs. linear

- Many graphs are on logarithmic scales; watch for this!
- This condenses wide-ranging information into a compact area
- Pay attention, because you could warp your intuition if you don’t appreciate the scale
- Log scales work in *factors of ten*
- A given vertical span represents a constant ratio (e.g., factor of ten, factor of two, etc.)
- An *exponential increase* looks like a *straight line* on a logarithmic scale

Example Plots



Exponential plot is curved on linear scale, and straight on a logarithmic scale

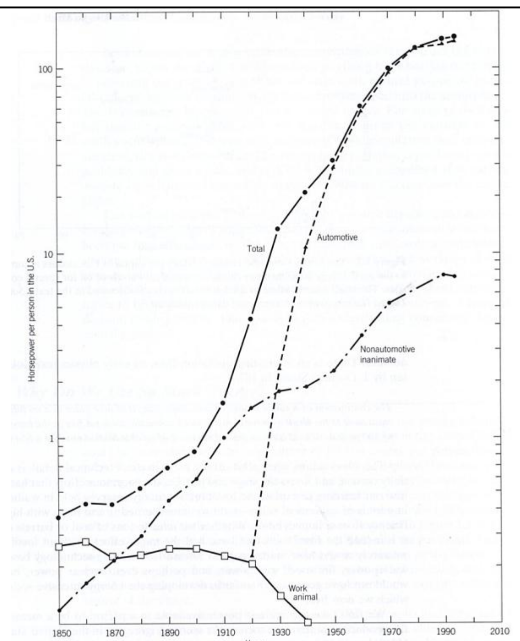
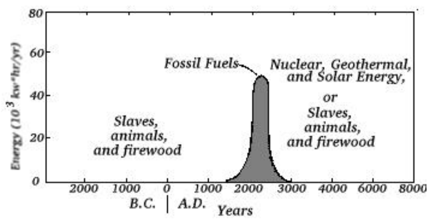


Figure 1.4 Horsepower per capita of all prime movers in the United States since 1850. Only a small fraction of this available horsepower is in use at any given time. (*Source: Historical Statistics of the United States, Colonial Times to 1970; Statistical Abstracts of the United States 2003*. Washington, D.C.: U.S. Department of Commerce, Bureau of the Census.)

A brief history of fossil fuels



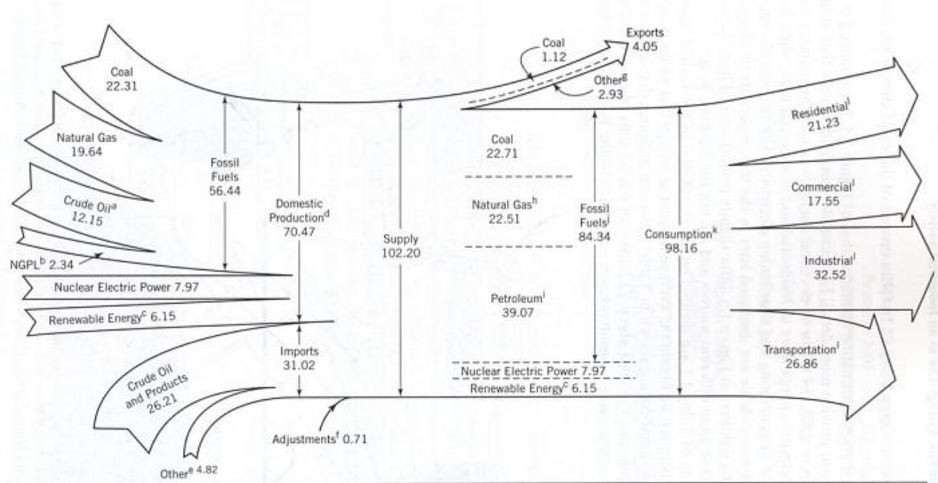
- Here today, gone tomorrow
- What will our future hold?
  - Will it be back to a simple life?
  - Or will we find new ways to produce all the energy we want?
  - Or will it be somewhere in the middle

Source	10^{18} Joules/yr (~QBtu/yr)	Percent of Total
Petroleum*	158	40.0
Coal*	92	23.2
Natural Gas*	89	22.5
Hydroelectric*	28.7	7.2
Nuclear Energy	26	6.6
Biomass (burning)*	1.6	0.4
Geothermal	0.5	0.13
Wind*	0.13	0.03
Solar Direct*	0.03	0.008
Sun Abs. by Earth*	2,000,000	then radiated away

Global Energy: Where Does it Come From?

* Ultimately derived from our sun

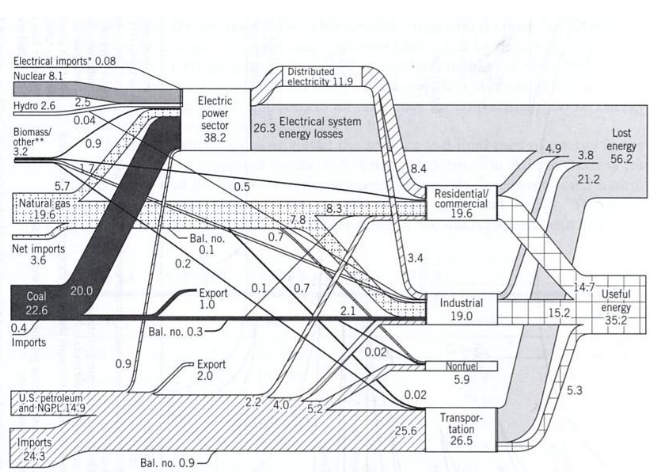
Courtesy David Bodansky (UW)



[a] Includes lease condensate.
[b] Natural gas plant liquids.
[c] Conventional hydroelectric power, wood, waste, ethanol blended into motor gasoline, geothermal, solar, and wind.
[d] Includes –0.09 QBtu hydroelectric pumped storage.
[e] Natural gas, coal, coal coke, and electricity.
[f] Stock changes, losses, gains, miscellaneous blending components, and unaccounted-for supply.
[g] Crude oil, petroleum products, natural gas, electricity, and coal coke.
[h] Includes supplemental gaseous fuels.
[i] Petroleum products, including natural gas plant liquids.
[j] Includes 0.05 QBtu of coal coke net imports.
[k] Includes, in QBtu, –0.09 hydroelectric pumped storage; –0.24 ethanol blended into motor gasoline, which is accounted for in both fossil fuels and renewable energy but counted only once in total consumption; and 0.02 electricity net imports.
[l] Primary consumption, electricity retail sales, and electrical system energy losses, which are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales.

Notes: • Data are preliminary. • Totals may not equal sum of components due to independent rounding.

Figure 1.5 Energy flow from source to use in the United States in 2003 in units of QBtu. (*Source*: Washington, D.C.: U.S. Department of Energy, Energy Information Administration, *Annual Energy Review*, 2003.)



*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

Figure 1.6 Energy flow in the United States in 2002 in units of QBtu, arranged to separate out useful energy from lost energy. (*Source*: Lawrence Livermore National Laboratory (2004) and United States Energy Information Administration, Annual Energy Review 2002.)

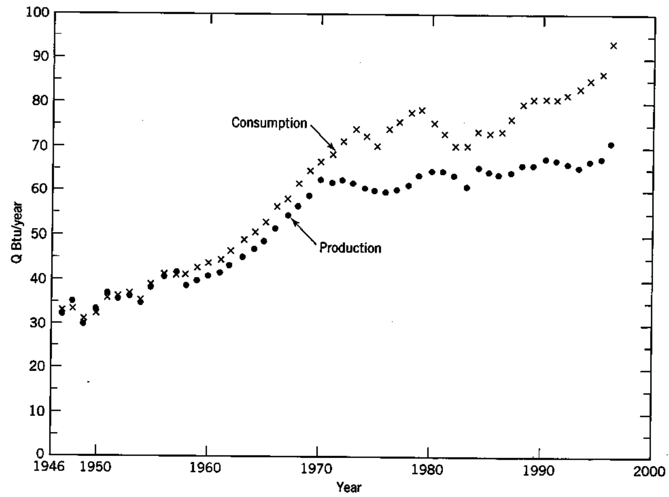
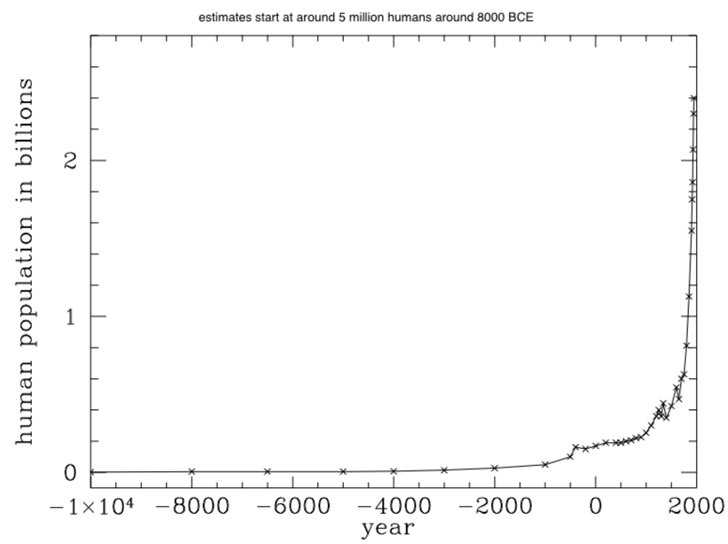
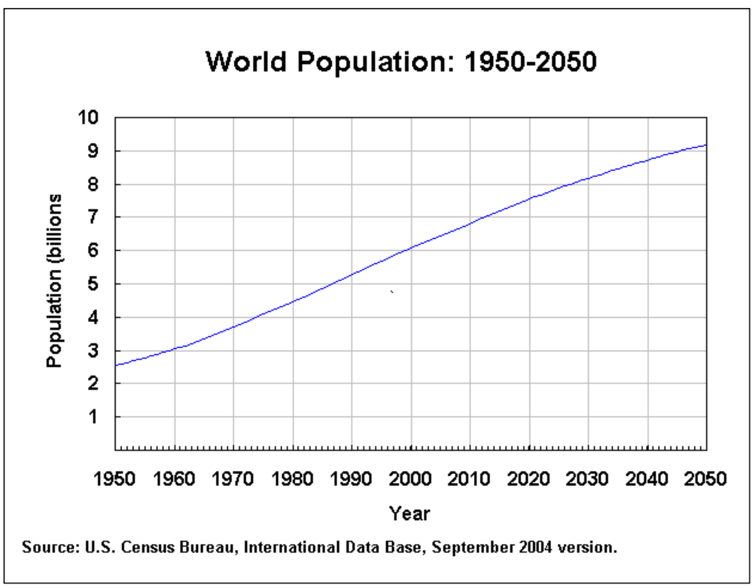


Figure 1.7 The total energy consumption and production in the United States since 1947 in quadrillion British Thermal Units (QBtu) per year. (*Source*: Washington, D.C.: U.S. Department of Energy, Energy Information Administration, *Annual Energy Review 1996.*)

Why do we use so much energy?


estimates start at around 5 million humans around 8000 BCE
human population in billions
0
1
2
−1×10⁴
−8000
−6000
−4000
−2000
0
2000
year


World Population: 1950-2050
Population (billions
10
9
8
7
6
5
4
3
2
1
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
Year
Source: U.S. Census Bureau, International Data Base, September 2004 version.

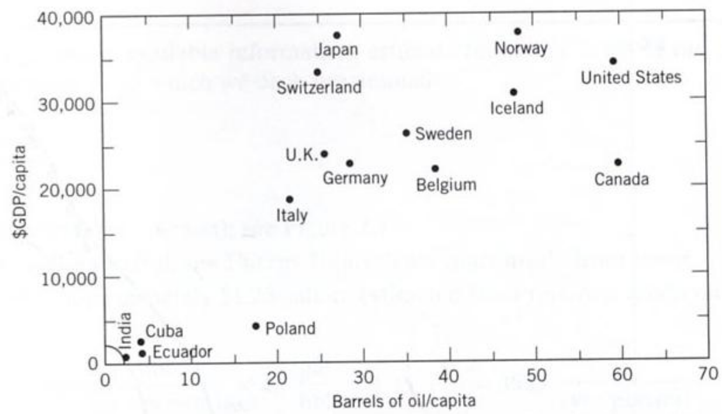
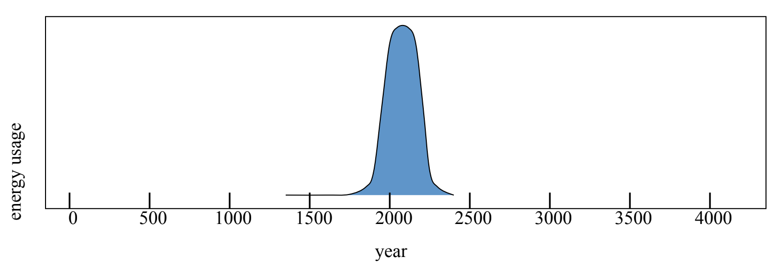


Figure 1.3 The Gross Domestic Product (GDP) per capita in U.S. dollars is compared to the total energy consumed per capita in equivalent barrels of oil for several countries. The small quarter-circle at the lower left corner is discussed in the text. (*Source*: *United Nations Statistical Yearbook*; data January 2003.)

We live in a special time and place…

- We use almost 100 times the amount used by the rest of the world (by population)
- This phase has only lasted for the last century or so
- Most of our resources come from fossil fuels presently, and this has a short, finite lifetime
- Fossil fuels formed from solar energy over 300 million years, will be used up in a few centuries!



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 =Energy: more than just unpleasant tasks

- In physics, the definition of work is the application of a *force through a distance; Energy is needed to do it*

$$W = F \cdot d$$

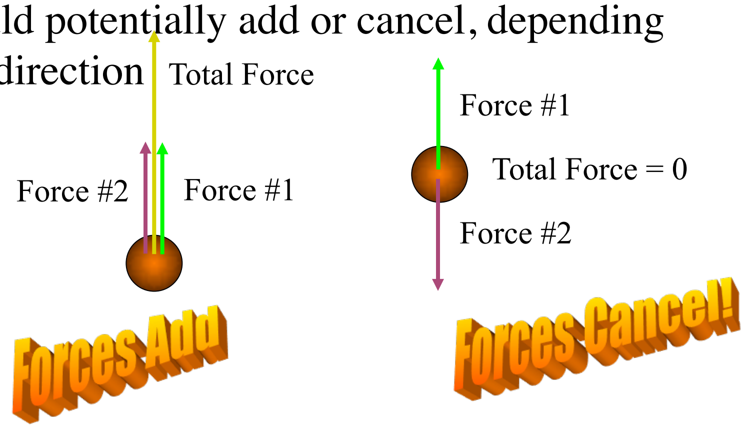
- W is the *work* done = energy used
- F is the *force* applied
- d is the *distance* through which the force acts
- Only the force that acts in the direction of motion counts towards work

Okay, what is Force, then

- Force is a pushing/pulling agent
- Examples:
  - gravity exerts a downward force on you
  - the floor exerts an upward force on a ball during its bounce
  - a car seat exerts a forward force on your body when you accelerate forward from a stop
  - the seat you're sitting in now is exerting an upward force on you (can you feel it?)
  - you exert a sideways force on a couch that you slide across the floor
  - a string exerts a centrally-directed (centripetal) force on a rock at the end of a string that you're twirling over your head
  - the expanding gas in your car's cylinder exerts a force against the piston

Forces have Direction

- In all the previous examples, force had a direction associated with it
- If multiple forces act on an object, they could potentially add or cancel, depending on direction



When net force is not zero

- When an object experiences a non-zero net force, it *must* accelerate
- Newton's second law:

  $F = m{\cdot}a$ Force = mass times acceleration
- The same force makes a small object accelerate more than it would a more massive object
  - hit a golf ball and a bowling ball with a golf club and see what happens

Question

- A 150 lb person is standing still on the edge of a cliff. What is the total force on the person?

A. zero
B. 150 lb
C. Can't say from this info

Question

- A 150 lb person jumps (or was he pushed?) off a cliff and is falling to their death. What is the total force on the person?

A. zero
B. 150 lb
C. Can't say from this info

But what is acceleration?

- This is getting to be like the "hole in the bucket" song, but we're almost there…
- Acceleration is *any* change in *velocity* (speed *and/or* direction of motion)
- Measured as rate of change of velocity
  – velocity is expressed in meters per second (m/s)
  – acceleration is meters per second *per second*
  – expressed as m/s^2 (meters per second-squared)

Putting it back together: Units of Energy

- Force is a mass times an acceleration (F=ma)
  - 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 (W=Fd)
  - 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 Zoo of Units

- The *main metric unit* of energy is the Joule, and most of the world uses this, but many others exist:
- The calorie is 4.184 Joules
  - raise 1 gram (c.c.) of water one degree Celsius
- The Calorie (kilocalorie) is 4,184 J (used for food energy)
  - raise 1 kg (1 liter) of water one degree Celsius
- The Btu (British thermal unit) is 1,055 J (roughly 1 kJ) or about 1/4 Calorie, or chemical energy of one match
  - raise 1 pound of water one degree Fahrenheit
- The kilowatt-hour (kWh) is 3,600,000 J = 3600 kJ or 860 Calories (used for electrical energy)
  - one Watt (W) is one Joule per second
  - a kWh is 1,000 W for one hour (3,600 seconds)
- Can also use "barrel of oil", "ton of coal", 1000 cubic feet of natural gas, gram of Uranium, or amount of any energy containing source, etc.

ENERGY CONVERSION FACTORS

- 1kWh = 862 Cal = 3413 Btu = 3.6 MJ
- 1 Cal = .0016 kWh = 3.97 Btu = 4184 J
- 1 Btu = .252 Cal = .000293 kWh = 1055 J
- 1 ft-lb = 1.36 J
- 1 gal gasoline = 31000 Cal = 36.6 kWh =125000 Btu = 132 MJ
- 1 bbl oil = 1.5M Cal = 5.8 M Btu = 1700 kWh =6.1 GJ
- 1000 cf nat gas = 260,000 Cal = 1M Btu = 300 kWh= 1GJ = 10 therm
- 1 ton coal = 6.7M Cal = 27 M Btu = 7800 kWh = 28GJ
- 1 Qbtu = 300 G kWh = .17 G boe
- POWER = ENERGY/TIME CONVERSIONS:
- 100 Qbtu/yr = 3.35 TW = 172. G boe/year
- 1 Cal/hr = 1.16 W = 3.97 Btu/hr
- 1 horsepower = 746W = 550 ft-lb/sec
- boe = barrel of oil equivalent, Cal = kcal = 1000 cal, J=Joule (metric), kWh = kilo Watt hr, W = Watt (metric)
- k=kilo, M=Mega=10^6, G=Giga=10^9, T=Tera=10^{12}, P=Peta=Q=Quadrillion=10^{15}

The Physics of Energy Formula List

- Lots of forms of energy coming fast and furious, but to put it in perspective, here's a list of formulas:

Energy Form	**Energy Formula**
Work	$W = F \cdot d$ *(Force times distance)*
Kinetic Energy	K.E. = $\frac{1}{2}mv^2$ (mass times velocity squared)
(Grav.) Potential Energy	$E = mgh$ *(mass times height times* $10 m/s^2$*)*
Heat Energy	$\Delta E = c_p m \Delta T$ *(mass times change in temperature times heat capacity)*
Mass energy	$E = mc^2$ (mass times speed of light squared)
Radiative energy flux	$F = \sigma T^4$ (temperature to the fourth power times a constant)
Power (rate of energy use)	$P = \Delta E/\Delta t$

Kinetic Energy

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

  $K.E. = \frac{1}{2}mv^2$

- 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:

  $$K.E. = \tfrac{1}{2}\times(0.145\ \text{kg})\times(30\ \text{m/s})^2$$
  $$= 65.25\ \text{kg}\cdot\text{m}^2/\text{s}^2 \approx 65\ \text{J} = 0.016\ \text{Calories!}$$

- 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:

  $$K.E. = \tfrac{1}{2}\times(0.00567\ \text{kg})\times(5\ \text{m/s})^2$$
  $$= 0.07\ \text{kg}\cdot\text{m}^2/\text{s}^2 = 0.07\ \text{J}$$

More numerical examples

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

  K.E. = ½×(1500 kg)×(30 m/s)^2

  = 675,000 kg·m^2/s^2 = 675 kJ

  Convert to Calories: 4.184 kJ = 1 Calorie

  675 kJ (1 Calorie/4.184 kJ) = 161 Calorie

- A 2 kg (~4.4 lb) fish jumps out of the water with a speed of 1 m/s (2.2 mph)

  K.E. = ½×(2 kg)×(1 m/s)^2

  = 1 kg·m^2/s^2 = 1 J

Question

1 m/s = 2.2 mph

- Kinetic energy is E = 1/2 m v^2 . Which has more energy?

A. 10 kg object going 100 m/s

B. 100 kg object going 10 m/s

C. 1 kg object going 1000 m/s

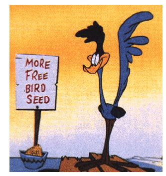
D. 1000 kg object going 1 m/s

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

$$F = mg \quad \text{(note similarity to } F = ma\text{)}$$

  - $g = 9.8$ m/s^2 on the surface of the earth; or 32 ft/s^2



- 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.
- Water in river or hydroelectric plant is using potential energy that it got from being lifted up when Sun (solar energy) evaporated the water

Question

- Potential energy is E = 10 m h (metric units) . Which has more energy?

A. 1 ton of water at a height of 100 ft

B. 100 tons of water at a height of 1 ft

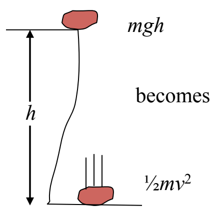
C. 200 lb (1/10 ton) of water at 1000 ft

D. All of the above have same energy

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??

  $\Rightarrow$ 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?

$$mgh = (70\text{ kg})\times(10\text{ m/s}^2)\times(10\text{ m})$$
$$= 7{,}000\text{ kg}\cdot\text{m}^2/\text{s}^2 = 7\text{ kJ}$$

7 kJ (1 Calorie/4.182kJ) = 1.6 Calories

This is amount of energy the diver used in climbing the stairs (actually more than this since some energy was wasted) They got that energy from the food they ate.

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. In British Units, 1 Btu heats 1 pound of water 1 degree Fahrenheit.
  - 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
- Drink a pint (16 oz) of ice cold water (or coke). It weighs about 1 pound. To heat it to body temperature (98.6 degrees minus 32 degrees or change of 66.6 degrees. Takes about 67 Btu. Convert to Calories: 1 Calorie = 1kJ = 4 Btu, so

  67 Btu (1 Calorie / 4 Btu) = 16.75 Calories. Since 16 oz of coke has 210 Calories and about 17 Calories are used just heating to your body temp you get less calories drinking it cold! (or drinking quart of cold water "burns" 17 Calories).

The Physics of Energy Formula List

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Heat Capacity

- Different materials have different *capacities* to hold 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)

Important in designing solar heated houses! Also reason it is cooler near the coast than inland!

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 $\rightarrow$ 700 W output!
- Shuttle puts out a few GW (gigawatts, or 10^9 W) of power!
- A big electrical power plant puts out around a GW. That is 1 Billion Joules per second. House takes a few kW (kilowatt)

Question

1 Calorie/minute = ? Watts

- Power is Energy used per second. P= energy/time. Which highest power?

A. Using 100 Calories in 10 minutes

B. Using 1000 Calories in 100 minutes

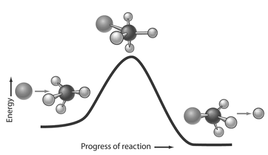
C. Using 10 Calories in 1 minute

D. Using 1 Calorie in 6 seconds

E. All of the above are the same power usage

Wind Energy

- Wind can be used as a source of energy (windmills, sailing ships, etc.)
- Really just kinetic energy
- Example: wind passing through a square meter at 8 meters per second
  - Each second we have 8 cubic meters
  - Air has density of 1.3 kg/m^3, so (8 m^3)×(1.3 kg/m^3) = 10.4 kg of air each second
  - $\frac{1}{2}mv^2 = \frac{1}{2}\times(10.4\text{ kg})\times(8\text{ m/s})^2 = 333$ J
  - 333 J every second → 333 Watts of available power per square meter (but to get *all* of it, you'd have to stop the wind)
- Stronger winds → more power (like v^2)



Chemical Energy

- Electrostatic energy (associated with charged particles, like electrons) is stored in the chemical bonds of substances, e.g. carbohydrates, hydrocarbons
- 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
  - typical molecules are tens of grams per mole→works out to typical numbers like several thousand Joules per gram, or a few Calories per gram (remember, 1 Cal = 1 kcal = 4187 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 (450 Cal/lb)
- Burning coal releases about 20 kJ per gram of chemical energy, or roughly 5 Cal/g (2300 Cal/lb)
- Burning gasoline yields about 39 kJ per gram, or just over 9 Cal/g (4000 Cal/lb)
- Very few substances over about 11 Cal/g
- (1 Cal/g = 453 Cal/lb)

Energy from Food

- We get the energy to do the things we do out of food (stored solar energy in the form of chemical energy).
- Energy sources recognized by our digestive systems:
  - Carbohydrates: 4 Calories per gram
  - Proteins: 4 Calories per gram
  - Fats: 9 Calories per gram (like gasoline) (9 is more than 4, so gain more weight eating same amount of fat than carbs or protein!)
  - Roughly 3500 Calories/pound in your body fat! Less in your protein (muscle, skin, etc.)

Our Human Energy Budget

- A 2000 Calorie per day diet means 2000×4184 J = 8,368,000 J per day
- 8.37 MJ in (24 hr/day) × (60 min/hr)×(60 sec/min) = 86,400 sec corresponds to 97 Watts of power
- Even a couch-potato at 1500 Cal/day burns 75 W
- More active lifestyles require greater Caloric intake (more energy)

Nutrition Labels

Whole Milk
Serving Size 8 fl oz (240mL)
Servings Per Container 2

Amount Per Serving	
Calories 150	Calories from Fat 70
	% Daily Value*
Total Fat 8g	12%
Saturated Fat 5g	25%
Cholesterol 35mg	12%
Sodium 125mg	5%
Total Carbohydrate 12g	4%
Dietary Fiber 0g	0%
Sugars 11g	
Protein 8g	

Vitamin A 6% • Vitamin C 4%
Calcium 30% • Iron 0% • Vitamin D 25%

* Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your calorie needs.

		2,000	2,500
	Calories:	2,000	2,500
Total Fat	Less than	65g	80g
Sat Fat	Less than	20g	25g
Cholesterol	Less than	300mg	300mg
Sodium	Less than	2,400mg	2,400mg
Total Carbohydrate		300g	375g
Dietary Fiber		25g	30g

- Nutrition labels tell you about the energy content of food
- Note they use Calories with capitol C
- Conversions: Fat: 9 Cal/g
  Carbs: 4 Cal/g
  Protein: 4 Cal/g
- This product has 72 Cal from fat, 48 Cal from carbohydrates, and 32 Cal from protein
  - sum is 152 Calories: compare to label
- 152 Cal = 636 kJ: enough to climb about 1000 meters (64 kg person)
- 1kwh = 860 Cal or about 1/4 lb body fat
- 1 gal of gas has 31,000 Calories

Mass-energy

- Einstein's famous relation:

  $E = mc^2$

  relates mass to energy
- In effect, they *are* the same thing
  - one can be transformed into the other
  - physicists speak generally of mass-energy
- Seldom experienced in daily life directly
  - Happens at large scale in the center of the sun, and in nuclear bombs and reactors
  - Actually *does* happen at barely detectable level in *all* energy transactions, but the effect is *tiny!*

$E = mc^2$ Examples

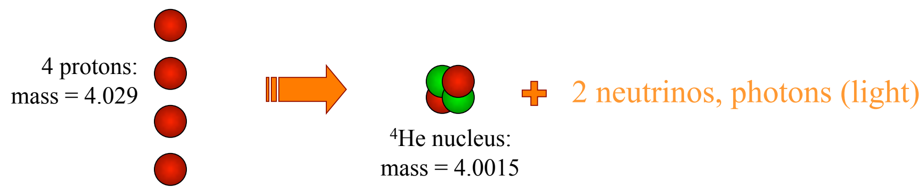
- The energy equivalent of one gram of material (*any composition!!*) is $(0.001\ \text{kg})\times(3.0\times10^8\ \text{m/s})^2 = 9.0\times10^{13}\ \text{J} = 90{,}000{,}000{,}000{,}000\ \text{J} = 90\ \text{TJ}$
  - Man, that's big!
  - Our global energy budget is equivalent to 1000 kg/yr (that's about 1 ton per year)
- If one gram of material undergoes a *chemical* reaction, losing about 9,000 J of energy, how much *mass* does it lose?

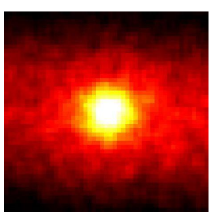
  $9{,}000\ \text{J} = \Delta mc^2$, so $\Delta m = 9{,}000/c^2 = 9\times10^3/9\times10^{16}$

  $= 10^{-13}$ kg (would we *ever* notice?)

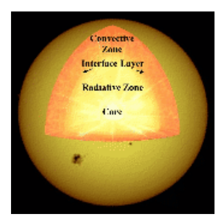
Solar Energy is Nuclear, Using $E = mc^2$

- Thermonuclear fusion reactions in the sun's center
  - Sun is 16 million degrees Celsius in its center
  - Enough energy to ram protons together (despite mutual repulsion) and make deuterium, then helium
  - Reaction per atom 20 million times more energetic than chemical reactions, in general





$E = mc^2$ in Sun



- Helium nucleus is *lighter* than the four protons!
- Mass difference is 4.029 - 4.0015 = 0.0276 a.m.u.
  - 1 a.m.u. (atomic mass unit) is 1.6605×10^{-27} kg
  - difference of 4.58×10^{-29} kg
  - multiply by c^2 to get 4.12×10^{-12} J
  - 1 mole (6.022×10^{23} particles) of protons $\rightarrow$ 2.5×10^{12} J
  - typical chemical reactions are 100-200 kJ/mole
  - nuclear fusion is ~20 million times more potent stuff!
  - Nuclear fusion is energy source of hydrogen bomb

Energy from Light

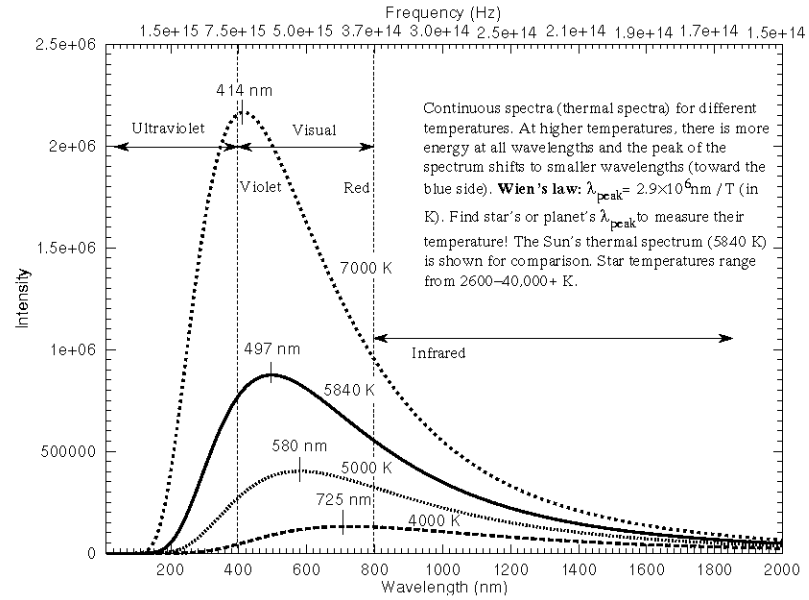
- The tremendous energy from the sun is released as light. So light carries energy.
- Light is one form of electromagnetic radiation: radio, microwave, infrared, visible light, ultra-violet, X-ray, gamma ray radiation
- Wiggling electrons create EM radiation: the faster the wiggling, the more energy and the higher the frequency
- Best way to get actual amount of energy in light is using "blackbody" radiation, or thermal radiation…
- All objects emit "light"
- The color and intensity of the emitted radiation depend on the object's temperature: hotter more radiation and color is "bluer"

Emitted Radiation's Color and Intensity depend on Temperature

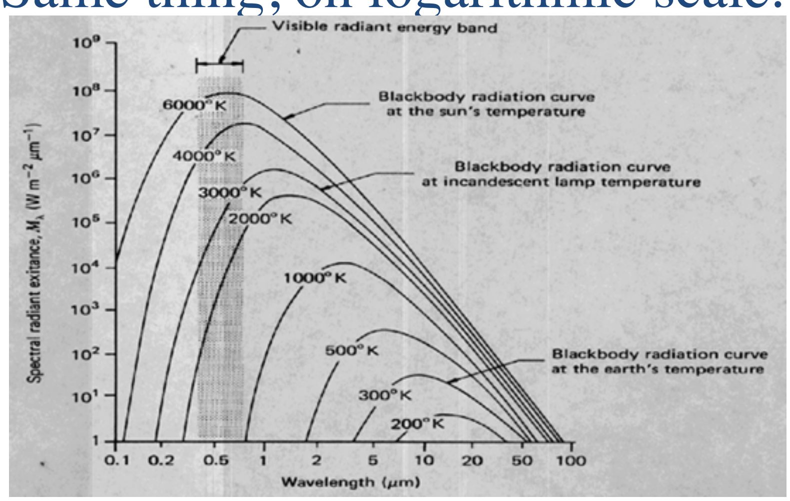
Object	Temperature	Color
You	~ 30 C	Infrared (invisible)
Heat Lamp	~ 500 C	Dull red
Candle Flame	~ 1700 C	Dim orange
Bulb Filament	~ 2700 C	Yellow
Sun's Surface	~ 5500 C	Brilliant white
Neutron Star	~ millions C	X-rays
Molecules in deep space	< -272C	Microwave or radio

The hotter it gets, the "bluer" the emitted light
The hotter it gets, the *more intense* the radiation (more energy)

“Blackbody”, or Planck Spectrum



Same thing, on logarithmic scale:



Sun peaks in visible band (0.5 microns), light bulbs at 1 µm, we at 10 µm.
(note: 0°C = 273°K; 300°K = 27°C = 81°F)

Okay, but how much energy?

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

  $F = \sigma T^4$ in Watts per square meter
  - the constant, σ, is numerically 5.67×10^{-8} W/°K^4/m^2
  - easy to remember constant: 5678
  - temperature must be in Kelvin:
    - °K = °C + 273
    - °C = (5/9)×(°F –32)
- Example: radiation from your body:

  $(5.67 \times10^{-8}) \times(310)^4 = 523$ Watts per square meter

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

Radiant Energy, continued

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

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

  Summing over entire surface area of sun gives

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

Electrical Energy

- Opposite charges attract, so electrons are attracted to protons. This holds atoms together.
- It takes energy to pull electrons off their atoms.
- Electrons want to get back home to their protons. They can only travel through conductors like wires, not through insulators like plastic, paper or wood. They will go through miles of wire to get home to their protons!
- This is how electricity works. The electron's energy can be stolen as it goes home. Can be used in many, many ways.
- Note electricity is not a primary source of energy. Energy (from burning coal, nat gas, from hydro, wind, nuke or solar) is used to pull of electrons and that energy can be moved through wires and got back at will.

And those are the major players…

- We've now seen most of the major energy players:
  - work as force times distance
  - kinetic energy (wind, ocean currents)
  - gravitational potential energy (hydroelectric, tidal)
  - chemical energy (fossil fuels, batteries, food, biomass)
  - heat energy (power plants, space heating)
  - mass-energy (nuclear sources, sun's energy)
  - radiant energy (solar energy)
  - electrical energy (energy of electrons separated from their atoms)

Conservation and Exchange of Energy

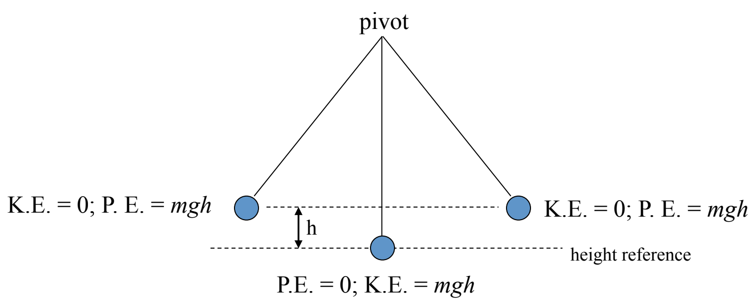
Nothing Comes for Free

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 amount of energy in the Universe is <u>constant</u>!!
- Don't we *create* energy at a power plant?
  - Oh that this were true—no, we simply *transform* energy at our power plants
- Doesn't the sun *create* energy?
  - Nope—it *exchanges* mass for energy
- Don't batteries give us new energy?
  - Nope, just convert stored chemical energy to electrical energy. Someone had to put that energy in there.

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 simple pendulum, in which a continual exchange goes on between kinetic and potential energy



Perpetual Motion

- Why won't the pendulum swing forever?
- It's hard 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

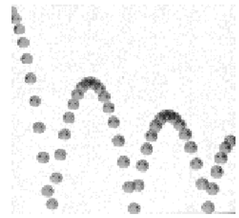
Some Energy Chains:

- A coffee mug with some gravitational potential energy is dropped
- potential energy turns into kinetic energy
- kinetic energy of the mug goes into:
  - ripping the mug apart (chemical: breaking bonds)
  - sending the pieces flying (kinetic)
  - into sound
  - into heating the floor and pieces through friction as the pieces slide to a stop
- In the end, the room is slightly warmer (heated by exactly the number of Calories originally stored in the potential energy).

Gasoline Example

- Put gas in your car, containing 9 Cal/g (31,000 Cal/gallon)
- Combust gas, turning 9 Cal/g into kinetic energy of explosion
- 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), and noise of engine (heating the air), etc.
- 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

  $F = \sigma T^4$

- 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

Rough numbers

- How much power does the earth radiate?
- $F = \sigma T^4$ for $T = 288°K = 15°C$ is 390 W/m^2
- Summed over entire surface area ($4\pi R^2$, where R = 6,378,000 meters) is 2.0×10^{17} W
- Human global production is about 13×10^{12} W (100 QBtu/yr = 3.3TW, World ~4 times more)
- 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

Examples

- Unit conversion:
  - 100 Btu into Calories: 100 Btu (1 Calorie/3.96 Btu) = 25 Cal
  - 100 Btu into Joules: 100Btu (1055 J/1 Btu) = 105,500 J = 1 x 10^5 J
  - 100 Btu into kWh: 100Btu (1 kWh / 3413 Btu) = 0.029 kWh
  - 10 gallons of gasoline into kWh: 10 gals (132,000,000 J/1 gal) (1 kWh/3,600,000 J) = 366 kWh
  - How many calories per hour does 100 W bulb use? 100 W = 100 Joule/sec (1 Cal/4184 J) (60 sec/ 1 min) (60 min/ 1 hour) = 86 Calories/hour. About what average person eats!
  - Gasoline is $3/gal. Electricity if $0.15/kWh. Which is more expensive? Convert $3/gal to $ per kWh. $3/gal (1 gal/36.6 kWh) = $0.08/kWh for gasoline. Gasoline is cheap in the USA!

Examples

- Power vs. Energy: (P=E/time; E = P t; t = E/P)
  - Car goes 60 miles in one hour and uses 3 gal of gas. What was total power in Watts? P=E/t, Power = (3 gal/1 hour) = 3gal/hr (36.6 kWhr / 1 gal) = 109 kW (1000W / 1 kW) = 109,000 W [Alternative method: 3 gal/hr (132,000,000 J/1 gal) (1 hr/3600 sec) = 110,000 J/sec = 110,000 W
  - 1000 W space heater is on for 3 hours. How much does it cost if electricity is $.15/kWh? E= P t. E = (1000 W)(3 hr) = 3000 W hr (1kW/1000W) = 3kWh ($.15/kWh) = $.45 [Alternative method: E = (1000 W)(3 hr) (3600 sec/1hr) = 10,800,000 Ws = 10,800,000 J (1 kWh/3,600,000J) = 3 kWh. Again 45 cents.
  - AAA Battery contains 3.3 Calories of chemical energy. How long can it run a 2 Watt light bulb? time = E/P. time = 3.3 Calories/2 W = 1.65 Cal sec/Joule (4184 J/1 Cal) = 6,900 seconds (1 hr/3600 sec) = 1.9 hours

Participation Questions (write on piece of paper with name and hand in)

The U.S. uses about 7 Gbarrels of oil each year. This could be converted into which of the following units?

- A. Joules
- B. Watts
- C. QBtu's
- D. Dollars $
- E. Any of the above

Participation Question

- If one barrel of oil contains 1700 kWh of energy, how many Watts is 7 Gbarrel/year

- A. 1400 GW (Giga Watts)
- B. 1.4 GW
- C. 11,900 W
- D. 11.9 MW
- E. 1×10^{11} W

Participation Question

- If the total yearly oil use in the U.S. is about 1400 GW, how many 1000 MW nuclear reactors will need to be built to replace all oil use with electricity?

A. A little more than one will be needed

B. Around 14

C. Around 140

D. Around 1400

E. Can't convert Watts to reactors; power vs energy

More Power Examples

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

  $mgh = (10\text{ kg})\times(10\text{ m/s}^2)\times(2\text{ m}) = 200\text{J}$

  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.)

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:
- $F_{drag} = ½c_D rAv^2$
- cD is a dimensionless drag coefficient
- r 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: $(kg/m^3)\cdot(m^2)\cdot(m/s)^2 = (kg\cdot m^2/m3)\ \cdot(m^2/s^2) =$

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

ENERGY CONVERSION FACTORS

- 1kWh = 862 Cal = 3413 Btu = 3.6 MJ
- 1 Cal = .0016 kWh = 3.97 Btu = 4184 J
- 1 Btu = .252 Cal = .000293 kWh = 1055 J
- 1 ft-lb = 1.36 J
- 1 gal gasoline = 31000 Cal = 36.6 kWh =125000 Btu = 132 MJ
- 1 bbl oil = 1.5M Cal = 5.8 M Btu = 1700 kWh =6.1 GJ
- 1000 cf nat gas = 260,000 Cal = 1M Btu = 300 kWh= 1GJ = 10 therm
- 1 ton coal = 6.7M Cal = 27 M Btu = 7800 kWh = 28GJ
- 1 Qbtu = 300 G kWh = .17 G boe
- POWER = ENERGY/TIME CONVERSIONS:
- 100 Qbtu/yr = 3.35 TW = 172. G boe/year
- 1 Cal/hr = 1.16 W = 3.97 Btu/hr
- 1 horsepower = 746W = 550 ft-lb/sec
- boe = barrel of oil equivalent, Cal = kcal = 1000 cal, J=Joule (metric), kWh = kilo Watt hr, W = Watt (metric)
- k=kilo, M=Mega=10^6, G=Giga=10^9, T=Tera=10^{12}, P=Peta=Q=Quadrillion=10^{15}