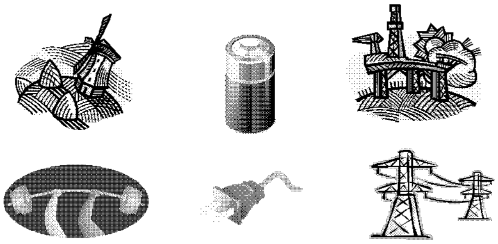
Energy & Power



Friday, November 6

When the universe became transparent, its temperature was like that of a star's **surface**.

T ≈ 3000 Kelvin

Earlier, its temperature was like that of a star's **center**.

T ≈ 10,000,000 Kelvin

In the centers of stars
(& in the early universe),
nuclear fusion takes place,
releasing **energy**.

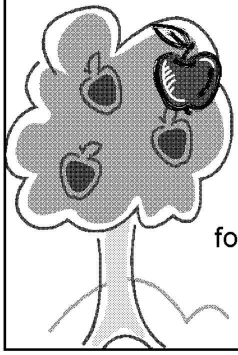
Seemingly simple question:

What is energy?

Textbook definition:
“Energy is the capacity to rearrange some part of the universe in certain ways.”

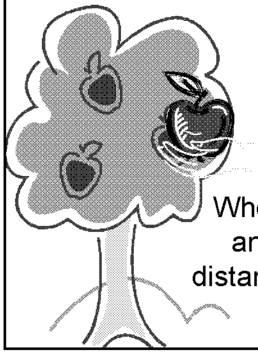
This is too vague to be useful.
Let’s look at concrete examples.

Apples fall to the ground once their stems break.



Why? Gravity exerts a force on them & accelerates them downward.

To lift an apple upward, you must exert a force on it.



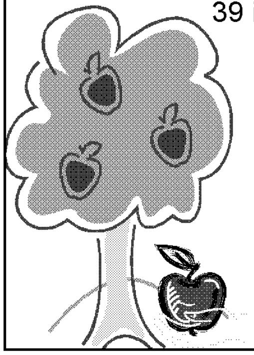
When you exert a force on an object through some distance, you are doing **work**.

Work = Force times distance.

Unit of **force** = 1 kg meter / sec^2
= 1 Newton = about 4 ounces

Unit of **distance** = 1 meter
= 39 inches

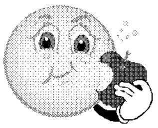
Unit of **work** = 1 kg meter^2 / sec^2
= 1 **Joule**



When you lift a quarter-pound apple through a height of 39 inches, you are doing **1 joule** of work.

(One joule is not a lot of work.)

New definition:
"Energy is the capacity to do work."



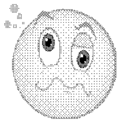
For instance, you can gain the energy to lift apples by eating apples.

Digesting a quarter-pound apple releases 50 food calories (200,000 joules) of energy.

James Joule
(1818-1889)

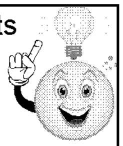
The joule is a unit of energy (in general) and a unit of work (in particular).

Other units of energy are calories, kilowatt-hours, BTUs, barrels of oil, kilotons of TNT…



I'll stick with joules.

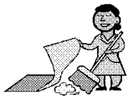
James Joule is honored by scientists because he helped to develop a **REALLY BIG IDEA**:



The **law of conservation of energy**, alias the **1st law of thermodynamics**.

Law of conservation of energy:
Energy can't be created or destroyed.
It can only change form.

If you start with 1 joule of energy, you must end with 1 joule.



Example:
Sunlight contains energy.
Each photon has an energy $E = \underset{\text{Planck's constant}}{h} \times \underset{\text{frequency}}{f}$.

If light is absorbed by water, the energy increases the kinetic energy of the water molecules: $E = \frac{1}{2} \underset{\text{mass of molecule}}{m} \underset{\text{speed of molecule}}{v}^2$.

The sum of the kinetic energy of all the randomly moving water molecules is the **thermal energy** of the water.

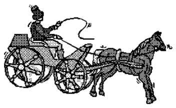
To have a large thermal energy, an object must have **(1)** a high temperature & **(2)** many molecules and atoms.

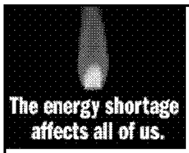
Energy vs. **Power**

Power is the **rate** at which energy is converted from one form to another.

Units of **power** = 1 Joule/second
= **1 Watt**

(1 horsepower = 746 watts)





Question:
If energy can't be destroyed, why do people whine about "energy shortages"?

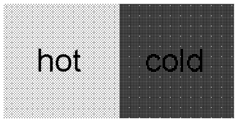
Answer:
Some forms of energy are more useful (better able to do work) than other forms.

First law of thermodynamics:
Energy can't be created or destroyed.

Second law of thermodynamics:
Disorder (technically called "entropy") increases.

Orderly (low entropy) state:

fast particles on one side



slow particles on other side

Disordered (high entropy) state:

Energy flows from regions of high thermal energy density to regions of low thermal energy density.

(The hot get colder and the cold get hotter.)

The flow of energy from hot regions to cold can do work.

Once a system is of uniform energy density, it can't do any more work.

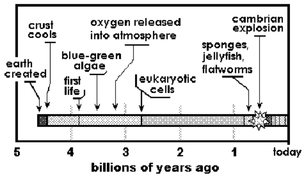
We don't have energy shortages; we have **entropy surpluses**!

Question:
Why do stars shine?

Short answer:
Stars shine because they are hot.

Follow-up question:
Why don't stars cool down?

There's a continuous fossil record of life on Earth for over 3 billion years.



Sun's luminosity (wattage, power) can't have been wildly variable – if it had, life would have scorched or frozen.

Sun must have an internal power source to replace the energy carried away by photons.

What's the power source?

The Sun's mostly hydrogen – what about burning hydrogen?

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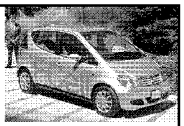
2 H + O → H_2O + energy



Burning 1 kilogram of hydrogen releases 1.4×10^8 joules of energy.

Sun's mass = 2×10^{30} kg.

(1.4×10^8 joules/kg) × (2×10^{30} kg)
= 2.8×10^{38} joules

The Sun throws away energy at a rate
$L_{sun} = 3.9 \times 10^{26}$ watts
$= 3.9 \times 10^{26}$ joules/sec.

Time to "burn up" the Sun =
2.8×10^{38} joules / 3.9×10^{26} joules/sec
$= 7.2 \times 10^{11}$ seconds

= 23,000 years

We need a power source that gives
us more bang for the buck
(more joules for the kilogram…)

The Sun's mostly hydrogen –
what about **nuclear fusion**,
converting hydrogen into helium?

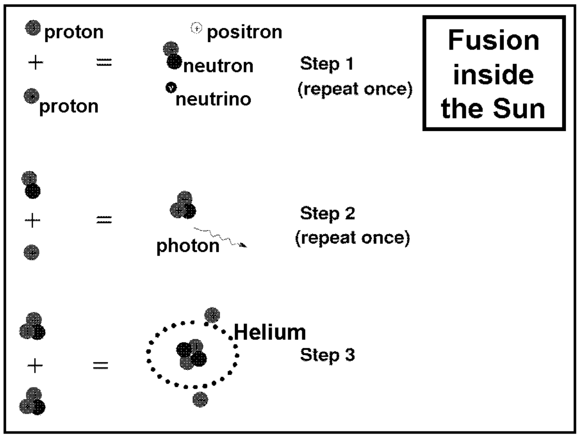
4 H → He + a **lot** of energy

Fusing 1 kg of hydrogen into helium
releases 6.2×10^{14} joules of energy.

That's 4.5 million times what you'd
get by burning the hydrogen.

Sun's hydrogen supply adequate for
billions, not thousands, of years.

Fusion inside the Sun



The fusion chain starts with combining two protons.

Protons are positively charged; overcoming their electrostatic repulsion requires high speeds.

T > 10 million Kelvin.

Monday's Lecture:

Stars as Nuclear Reactors

Reminders:

Have you read chapters 1 – 8 ?
Have you picked up your corrected problem sets & midterm?
Problem Set 5 is due on Friday the 13th.