ENERGY MATTERS!   A PHYSICS PERSPECTIVE

by Carl Ahlers

Energy and Matter : $E = mc^2$
neither can be destroyed
neither can be created (only changed to another form)

Energy is such a common concept. We talk about it everyday.
"I have installed an **energy** efficient heater"
"We talk about **energy** exports and **energy** policies.
And know that soft drinks hold lots of **energy** and have to turn off the lights to save **energy**.

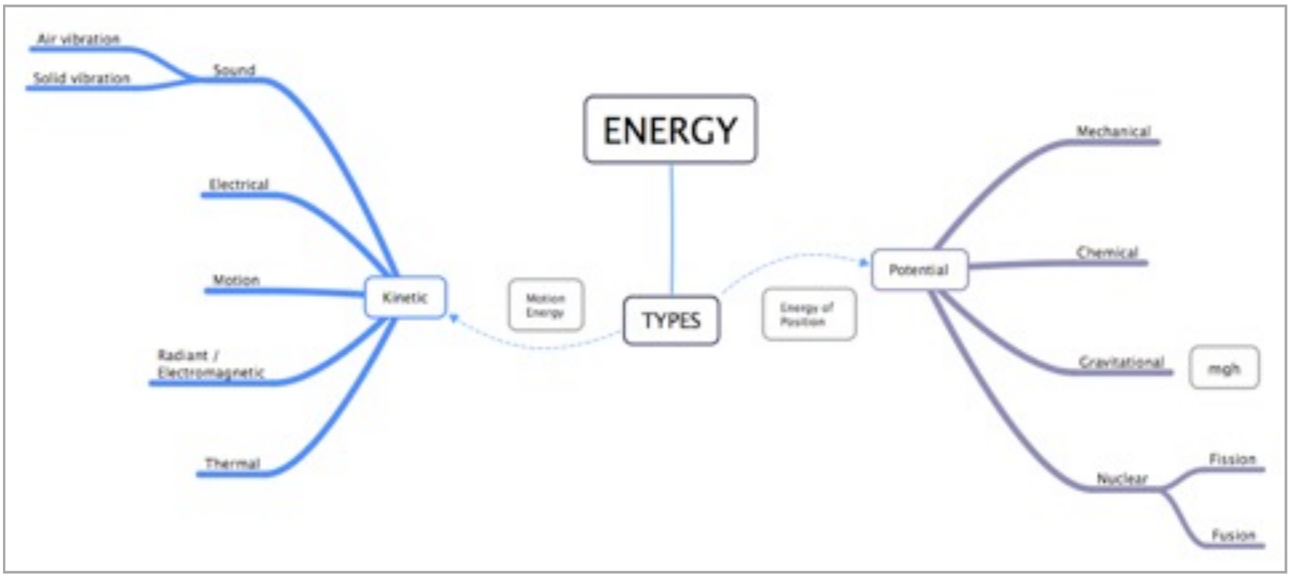
But what is Energy?

Energy is the ability or capacity to do work.
(To move an object against a resisting force).

- Has wind got energy?
- And a stretched rubber band?
- Does an unlit match have energy?
- And a wooden icy-pole stick?

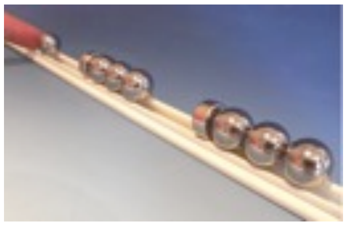
The answer is that all of the above contains energy.
Wind is made up of moving air that has got kinetic energy, a stretched rubber band holds potential energy because of the position of its molecules and the match has chemicals with energy captured in the chemical bonds, a form of potential energy. Even the icy-pole stick holds chemical energy in its cellulose molecules.

Every single kind of energy we can list, can be classified as either **kinetic** or **potential energy**.
Potential energy: the energy an object has due to the position or shape of the object.
Kinetic energy: the energy something has by virtue of its motion.



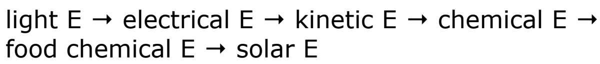
First Law of Thermodynamics (Conservation of Energy)
Energy can be transformed but cannot be created or destroyed
or
In a closed system, the total amount of energy remains constant.
You can't get something for nothing. And this rules out perpetual motion machines too!

Demonstration:



Newton's cradle, Collision Spheres, Magnetic Accelerator, AstroBlaster, Euler's Disk, Levitron

Energy is not stagnant. It flows! In an ideal ecosystem energy flows and matter cycles.
Let's have a look at one such an energy flow:
Shake a Faraday torch and have the students identify & list all the types of energies in the cycle and figure out what the origin is of the light energy they see.



Faraday's torch

When we say we <u>consume</u> energy, we actually mean "<u>convert</u> energy".
"We use 20 kWh electricity per day" means we have converted 20 kWh electrical energy per day to other useful forms of energy required around our house . . . and in doing so we have wasted huge amounts of heat energy that dissipated into the environment"

So how much is **one Joule**?
The amount of energy required to lift a mass of 100 g, 1 meter against gravity.

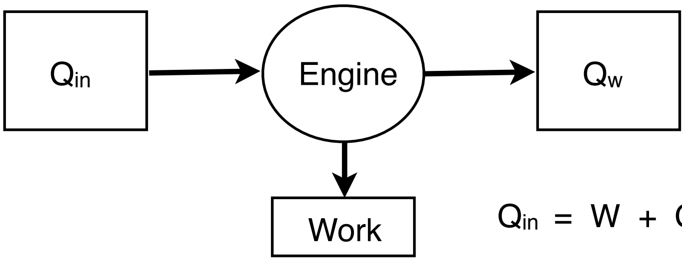
In 2008 the world energy consumption per person per day was 209 MJ (58.3 kWh). This is the same as the energy equivalent in 4.5 litres of petrol. But as only 8 MJ is required per person as food energy per day (UN estimate) the other 201 MJ was used to support our quality of life, eg. transport, heating, electricity, manufacturing, etc. *That's 25x of our food intake!*

Let's have a look at how effective engines convert energy.

The human heat engine. If I eat a Snickers bar containing 1.118 kJ energy. Does this mean I have gained enough energy to lift a 100 g ball 1,118,000 times?
No! Not close to that. The average person can make between 9 - 15% of his energy intake available as physical work. Most of your energy gets downgraded and wasted as heat.
Why?

Because of the existence of the Second Law of Thermodynamics . . .

Second Law of Thermodynamics
No conversion in a heat engine can be 100% efficient.
During such a conversion, the entropy of the surrounding closed system will increase.



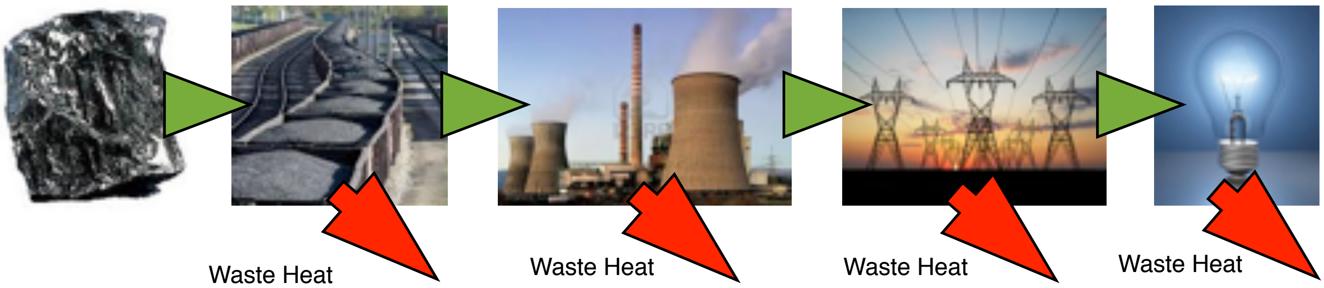
$Q_{in} = W + Q_w$

Efficiency = $\frac{\text{Energy out}}{\text{Energy in}}$ x 100%

Candle converting chemical to light energy	0.03%
Steam locomotive	18%
Mono-crystalline solar panel	16%
Car engine running on petrol	24%
Conventional coal fired power station	32%
Combined cycle gas turbine (modern power station)	50%

But **total system efficiencies** are much worse:
From coal chemical energy to light energy the efficiency is only 1.6%

1 kg of coal	**28.0 MJ**
- 2.5% in mining & transport	27.3 MJ
- 65% in coal power plant	9.56 MJ
- 7.5 % transmission in wires	8.84 MJ
- 95% electricity to light (incandescent bulb)	**0.44 MJ**



Energy is downgraded to "waste heat" at every conversion along the way (as it conforms to the second Law). More molecules in the "system" acquire energy so energy is dispersed ➜ increase in entropy!

As energy flows the Second Law states that no conversion can be 100%. This is because all natural spontaneous processes are driven by an increase in "energy distribution" (entropy). We encounter this everyday: Heat does not stay in our hot coffee but flows spontaneously to the cooler mug and air surrounding it. By doing this the thermal energy of the mug and air molecules are increased, and the entropy of the system has increased. This is predicted and dictated by the second Law.
When energy flows between two objects with different temperatures, we observe it as **heat**. The energy flows naturally from the warmer to the colder object. Objects cannot possess heat, heat is simply energy that flows.

To sum it up:
Energy can not be destroyed, only be turned into another form in never a 100% efficient transition.


Demonstration of heat engines: Drinking Bird, Stirling Engine & Thermoelectric Engine
All require a temperature differential to create mechanical or electrical energy.

Temperature & Kinetic Energy

Let's investigate the influence of temperature on molecular level. The scientific molecular model states that the molecules of all substances are in constant motion.

Demo: Put glasses of hot and cold water side by side. Place a drop of food colouring in each and see what happens.

From this we can conclude that a collection of hot molecules has more kinetic energy than an equal number of cold molecules. Temperature is thus an indication of the **average kinetic energy** of the molecules.

Demo: Take an empty wine bottle and a 10^{c} coin. Place the bottle in the freezer or in ice water for 30 minutes. The air molecules in the bottle will loose kinetic energy and move slower. Remove the bottle from the freezer and set it on a flat surface. Wet one surface of the coin and place it, wet side down, on top of the cold bottle. Check that it completely covers the opening. Watch closely. Accelerate the process by clasping the bottle with your hands.

What has happened? The cold air inside the bottle is denser and contains more molecules per volume than the room temperature air on the outside. As the air molecules inside the bottle heat up they move faster and faster, hitting the glass sides and coin more often. This increases the inner pressure and lifts the coin and a few air molecules escape. This happens until the air pressure on the outside is equal to the air pressure on the inside when both gases are at room temperature (= equilibrium).

Heat and Radiation, Absorption, Conduction & Convection

When heat transfers through direct contact between molecules of different substances, we call it **conduction**. This happens when you stick your hand in hot water. The fast moving water molecules hit your hand and transfer energy to your molecules, which increase their thermal energy.
When we step into sunlight, we warm up due to **radiation**. As their is empty space between us and the Sun, conduction is not possible. But light can transverse empty space and one specific part of the Sun's spectrum, infrared light, can heat things up through radiation.

Another way in which heat can transfer is via the movement of air or water molecules - **convection**. Cold molecules are more closely packed and will push warmer molecules that have a lower density to the top.



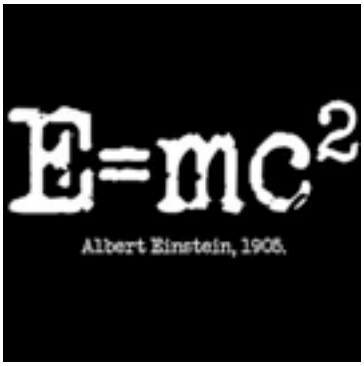
Demonstration: Ice melting blocks, Solar cooker, Solar collector tube

One of the best inventions of the decade is the **solar thermal collector tube**, the most efficient thermal collector on the market. Consisting of a strengthened borosilicate glass tube with double walls, the area between the inner and outer walls are evacuated. This acts as a thermos to keep heat from escaping into the atmosphere via **conduction** & **convection**.

Images: Solar Panels Plus

The outer wall is fully **transparent** to allow solar energy to pass through unimpeded. The inner layer is treated with a selective black optical coating which absorbs IR energy **radiation** with minimal **reflection**. The inner and outer walls are fused at high temperatures and all air is pumped from the space between them creating the thermos effect. Heat loss is further reduced by the low-**emissive** nature of the type of glass that is used. Because they are round, the tubes act as passive tracking solar collectors, maximizing their performance. These properties allow the tube to run on diffused sunlight with heat loss as low as 5°C overnight. In full sunlight **pasteurization** temperatures can be reached in less than 1 hour.

We have 500 mm solar vacuum tubes on order for use in classroom demonstrations. These tubes boil water in 45 minutes in full sun. Should be available in our 2012 Catalogue in February 2012.



But where does **E = mc²** fit into all of this?
Is it applicable to our everyday life?

This mass-energy relation is much more than a formula. Like all the equations of physics, it stands for an idea. It simply states that mass and energy are the same. Different views of the same entity. And it is not only applicable to nuclear processes.

Einstein was the first scientist to quantify the relationship between matter (mass) and energy.

The m in the equation needs some qualification. It actually indicates the "change in mass", Δm
All objects have a rest mass, m. But when an object starts moving Einstein's insight was to see that **its mass will increase**.
With how much? Simply the equivalent of its gain in kinetic energy! $E = {}^1/_2\, mv^2 = mc^2$

Example:
A 500 kg car moving at 100 km/h travels at 28 m/s. Its gain in kinetic energy is
$Ek = {}^1/_2\, mv^2 = (0.5)(500)(28)^2 = 196000$ J
So with how much does its mass increase?
Mass increase, $\Delta m = E/c^2 = 196000 \text{ J} / 9 \times 10^{16} = 2.18 \times 10^{-12}$ pg (Two trillionth of a gram !!)

We will never notice this increase as it is much too small, but it becomes significant once we get closer to the **speed of light** or when **huge amounts of energy** are involved.
We can safely stick to our use of Newton's Laws in our calculations.

But here are some everyday life implications of this famous equation:

- By heating a pot of soup you're adding 1×10^5 J of energy, increasing its mass by a billionth of a gram!

- If you lift a 1 kg object through 1 m, you are doing 10 J work on it. Its mass will increase by ${}^W/_{c}{}^2$ or 1.1×10^{-16} kg. This effect is much smaller than the mass of your fingerprints!

- The fission plutonium bomb that exploded at Nagasaki in 1945 gathered all its destructive energy from 1 gram of 'missing' plutonium mass: $E = (0.001)c^2 = 9 \times 10^{13}$ J

- If all the uranium-235 nuclei in a tonne of uranium were to undergo fission, the total mass would decrease by 6.6 grams.

- A moderately large power station can provide power at 1 GW. This equates to 3×10^{16} joule per year. So in such a power station 330 grams of matter will 'disappear' each year. In a nuclear power station the fuel rods will weigh 330 grams less at the end of the year. And in a coal fired power station if you could gather all the combustion products - fly ash, CO_2, nitrous oxides, sulphur oxides, etc. (Oh! if only we could) then you would miss 330 grams from the original mass of coal and oxygen consumed.