

Physics of Energy

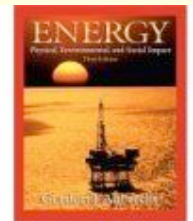
As we discussed Our society needs to find a sustainable energy solution that

- Fulfills global energy needs in the long term.
- Doesn't degrade the environment.

Premise of this course ... in order to come up with such a solution, we need to understand how energy works?

So, we are led to study the physics of energy.

Let's start with some things we already know about energy ...



Reading assignment in textbook - chapter 3 - work, energy & power

One thing we already know is that energy comes in many different forms ... we can make a list

- kinetic energy - the energy of motion
- thermal energy - heat
- chemical energy - stored in e.g. oil & other fossil fuels and in the food we eat
- electricity - running through our circuits, also in lightning
- light - how energy from the sun gets to earth
- nuclear energy - both fission and fusion (how the sun gets its energy)
- potential energy - if you're standing on a cliff

Another thing we know is that energy can move between these different forms ...

A few examples

We get hot if we lie out in the sun - energy in sunlight is converted to thermal energy in our bodies.



If we drop something off a cliff, it falls with increasing speed - gravitational potential energy is converted to kinetic energy.



If we turn on a light switch, the room lights up (& heats up too) - electrical energy is converted into light and heat.



If we rub our hands together, they get warm - chemical energy in our muscles is converted to kinetic energy and then through friction into heat.

Understanding the physics of energy means learning about two sorts of things.

1 - What general principles unify the physics of energy - applying to energy in all its different forms.

2 - How does each particular form of energy work.

We'll start with the general principles. These are known as the **laws of thermodynamics** - “thermo” means heat and “dynamics” means movement.

The study of thermodynamics began during the 19th century industrial revolution in Great Britain. Useful devices like steam engines - which turned heat into mechanical energy - were invented in this period. Engineers and scientists naturally wanted to understand the rules governing these machines and how to improve on them.



1st & 2nd Laws of Thermodynamics

1st law of thermodynamics- (roughly speaking) says the total amount of energy always stays the same. It can change between forms, but the total quantity of energy always stays the same.

Physicists call this principle “conservation of energy” and all known physical laws, e.g. gravity, electromagnetism, obey this principle.

For example, when a car brakes at a stop light, it's kinetic energy is transformed into heat by the friction in the brake pads. If we could add up all the energy before and after, we would find that it is unchanged.

Conservation of energy is actually violated by the expansion of the universe, but holds to excellent approximation here on Earth....



What physicists call “conservation of energy” is entirely different from what we normally call “energy conservation” - e.g. turning the lights off when you leave the room, or turning down the thermostat in order to “save energy.”

Indeed, the two notions of “conservation” seem to be at odds with one another. Why do we need to worry about “saving” energy, if the total amount always stays the same anyway?



This is where the 2nd law of thermodynamics comes in

2nd Law of Thermodynamics - implies that as energy is converted between different forms it always becomes less useful.

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For example, burning gas makes a car's engine go. The 1st law of thermodynamics tells us that energy is conserved in this process (in the physicist's sense).

Initially, chemical energy is stored in the gasoline. Afterwards we have the chemical energy stored in the combustion products plus the kinetic energy of the car, plus heat that gets dissipated by the car's radiator.



As an equation we could write this all down as ...

$$(CE)_{before} = (CE)_{after} + (KE)_{car} + (Heat)$$

energy after

energy before

If we let our foot off the gas, then eventually the car rolls to a stop, its kinetic energy worn down by friction and dissipated as heat.



We started with the chemical energy in the gasoline and ended up with a bunch of heat plus the chemical energy in the combustion products. Clearly the energy started out in a more useful form!

The 2nd law implies that something like this always happens.

This explains why “energy conservation” in the environmentalist’s sense is important. By not getting in our car and driving, we keep the energy stored in gasoline in a more useful form....

The precise statement of the 2nd law deals with something called **entropy**, which we’ll talk about later on. The 2nd law says that, in any physical process, entropy never decreases.

Roughly speaking, entropy measures the amount of disorder in a system. Increase of entropy implies that things fall apart, but never spontaneously come back together.

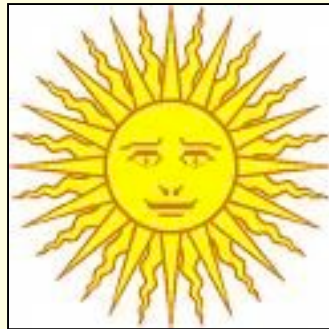


Yes →

← No



The 1st and 2nd laws of thermodynamics give us an understanding of the commonalities underlying how energy operates in all its many different forms to understand the ways we use energy in our society, we also need to work our way through each of these forms individually in more detail.



We'll start with kinetic energy - the energy of motion (*kinesis* is the greek word for motion). This is the simplest place for us to start building up a quantitative understanding of energy (i.e. in terms of mathematical formulas).

How much energy does a moving object have?

Depends on two things...

m = mass of object

v = velocity (or speed) of object

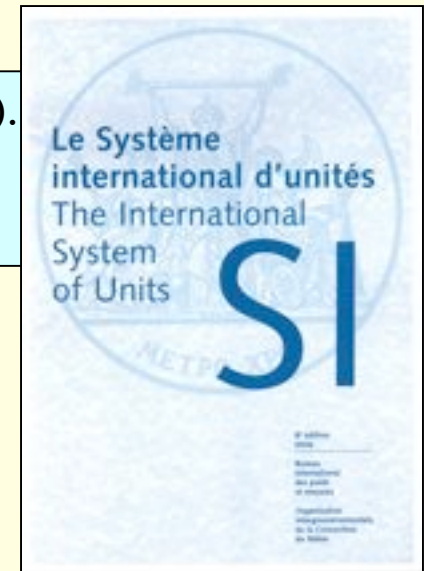


$$KE = \frac{1}{2}mv^2$$

Basic formula for
kinetic energy

We'll want to work out some examples, like how much kinetic energy does a car have going 65 mph, or a fastball going 100mph.... But first we need to ask how we measure energy? What units do we use?.

In this class we'll use the SI units (Le Systeme international d'Unites). SI units start with basic units for length (**meters**), mass (**kilograms**) and time (**seconds**).



We can easily make conversions from English units...

$$1 \text{ meter} = 3.28 \text{ feet}$$

$$1 \text{ kilogram} = 2.20 \text{ pounds}$$

So that

$$6.20 \text{ ft} = 6.20 \text{ ft} \left(\frac{1 \text{ m}}{3.28 \text{ ft}} \right) = 1.89 \text{ m}$$

In SI, most units for other quantities are built out of these 3 basic units - meters, kilograms and seconds

For example, speed is measured in meters per second, rather than miles per hour ...

Let's work out a conversion.

$$v = 65 \frac{\text{miles}}{\text{hour}} = 65 \frac{\text{miles}}{\text{hour}} \left(\frac{1600 \text{ m}}{\text{mile}} \right) \left(\frac{1 \text{ hour}}{3600 \text{ s}} \right) = 29 \frac{\text{m}}{\text{s}} = 29 \text{ ms}^{-1}$$

The SI unit for energy is called the **Joule** in honor of James Prescott Joule, a 19th century British physicist who made important contributions to understanding conservation of energy.

In terms of meters, kilograms and seconds, a Joule is given by

$$1J = 1\text{Joule} = 1\left(\frac{\text{kilogram} \cdot \text{meter}^2}{\text{sec ond}^2}\right) = 1\text{kgm}^2\text{s}^{-2}$$

This makes sense, if we think about the formula for kinetic energy

$$KE = \frac{1}{2}mv^2$$

If the mass m is given in kilograms and the velocity v is given in meters/second, then the kinetic energy comes out in Joules.

Example. What is the kinetic energy of a 1 ton car moving at 65mph?

First convert mass

$$1\text{ton} = 2000\text{lb} = 2000\text{lb}\left(\frac{1\text{kg}}{2.2\text{lb}}\right) = 910\text{kg}$$

and recall that

$$65\text{mph} = 29\text{ms}^{-1}$$

now use the formula for kinetic energy

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}(910\text{kg})(29\text{ms}^{-1})^2 = 380,000\text{J} = 3.8 \times 10^5\text{J}$$

Later on we'll calculate the energies of other things to compare to this...



Power is another closely related quantity that we'll need a unit for ...

Power is the rate at which energy is being used or generated.

The SI unit for power is called the Watt, after the Scottish engineer James Watt, one of the inventors of the steam engine.

$$1W = 1Watt = 1 \frac{Joule}{second} = 1Js^{-1}$$

A 100W light bulb uses 100 Joules of energy each second.



We also hear about Watts in the context of power plants ...

A 500 Megawatt power plant generates 500 million Joules of electric power per second.

The prefix Mega means million. Giga means billion.



Later on we'll learn what electricity is and how electric generating plants work

If you get a bill from the electric company at your home, they charge you for the amount of electric energy you use each month. Instead of using Joules, they measure the energy in **Kilowatt-hours**.

Recall that power is the rate of energy usage. So, we can write...

$$power = \frac{energy}{time}$$

Or equivalently

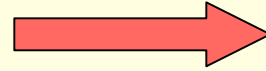
$$energy = (power) \cdot (time)$$

Kilowatt-hours are a unit of power times a unit of time, which gives a unit of energy. We can easily convert kilowatt-hours to Joules.

$$1Kw \cdot hr = (1000W)(3600s) = (1000 J/s)(3600s) = 3.6 \times 10^6 J$$



Now, let's talk about a second form of energy



Potential energy

Imagine you are standing on top of half dome in Yosemite valley, holding a rock in your hand.

The rock has no kinetic energy, but if you threw it off the cliff it would have quite a bit of kinetic energy by the time it hit the valley floor.

We say that the rock has potential energy. If **m** is the mass of the rock and **h** the height above ground, the potential energy of the rock is...



$$PE = mgh$$

What is **g** here?

g is known as the gravitational constant. It measures the strength of the Earth's gravitational pull on falling objects.

Galileo demonstrated that all objects fall the same way.

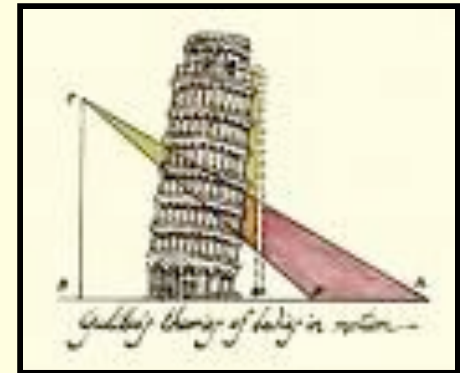
If two objects are dropped from the same height at the same time, then they will hit the ground at the same time (as long as other forces like air resistance are negligible).



Falling objects accelerate downwards at a rate of ...

$$g = 9.8m / s^2$$

Acceleration is the rate of change of velocity with time. So, the units of acceleration are the units for velocity divided by another factor of time.



More on acceleration & related physics...

2007 Ferrari F430

Weight: 3196 lb (1450 kg)

Acceleration: 0-62 mph in 4.0s

Top Speed: >196 mph (>315 km/h)

Fuel Economy city/highway 11/16 mpg



Let's calculate its acceleration in meters/(second)²

Basic physics result - if an object starts at rest at time $t=0$ and accelerates with a constant acceleration, its velocity increases linearly with time....

$$v = a \cdot t$$

↑
acceleration

If we want to figure out the acceleration, we can rewrite this as

$$a = v / t$$

The car accelerates, reaching a velocity of $v=62 \text{ mph} = 28 \text{ m/s}$ in $t=4 \text{ s}$, which gives

$$a = (28 \text{ ms}^{-1}) / (4 \text{ s}) = 7 \text{ ms}^{-2}$$

A little bit smaller than the gravitational acceleration of $g=9.8 \text{ m/s}^2$

While we're talking about acceleration, let's introduce another piece of basic physics ... **Newton's 2nd law**.

$$F = m \cdot a$$

Force equals mass times acceleration. If there is a net force on an object, it will accelerate. Conversely, if something is accelerating, there must be a force on it.



Back to gravity...the gravitational force (at the earth's surface) is

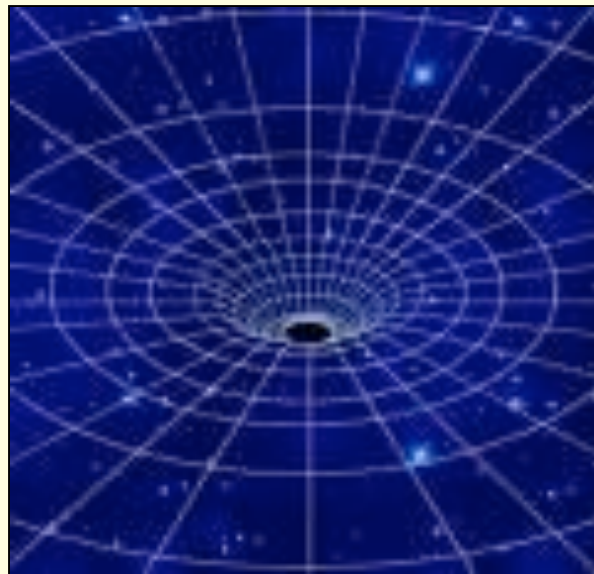
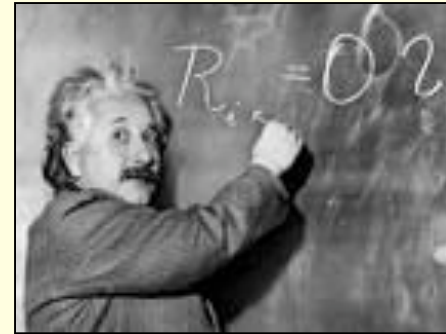
$$F = m \cdot g$$

Setting these two expressions equal, we see that the mass cancels giving

$$a = g$$

independent of the mass of the object.

The fact that the masses are the same in these two equations has very deep significance in physics. This “equivalence principle” led Einstein to his theory of gravity - general relativity - in which the gravitational force is a manifestation of the curvature of spacetime.



Finally, back to gravitational potential energy

We can check that potential energy indeed has the units of energy...

$$PE = mgh$$

If the mass is measured in kilograms and the height in meters
then the units of potential energy work out to be...

$$kg \cdot (ms^{-2}) \cdot m = kg \cdot m^2 \cdot s^{-2} = \text{Joules}$$

We can also check that falling objects satisfy conservation of energy.

If we drop something from a height **D** at time **t=0**, then it's position and velocities as functions of time are given by

$$h(t) = D - \frac{1}{2}gt^2 \quad v(t) = -gt$$

Now, let's calculate the total energy as a function of time.

$$E = KE + PE = \frac{1}{2}mv(t)^2 + mgh(t)$$

The result is actually independent of time and equal to the initial potential energy, demonstrating conservation of energy.

$$E = \frac{1}{2}(-gt)^2 + mg(D - \frac{1}{2}gt^2) = mgD$$

A practical application of potential energy How to store energy without a battery?

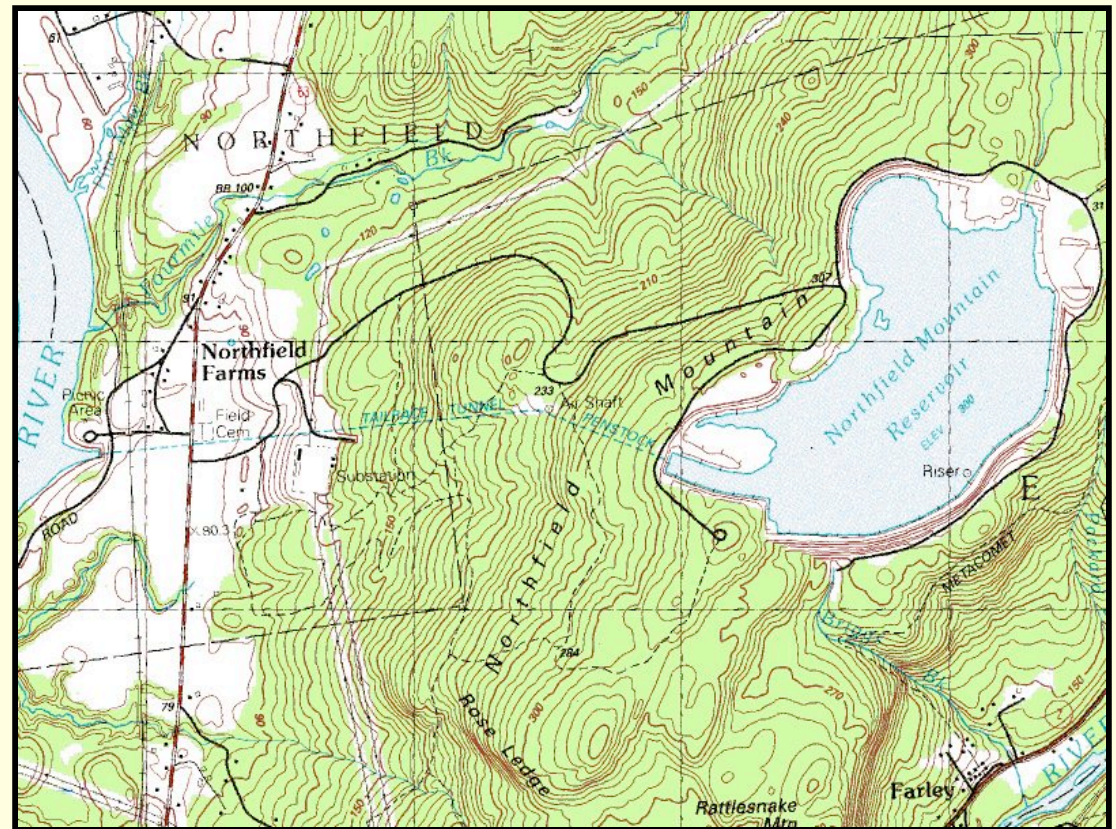
We'll see that one problem with electricity is that it's difficult to store. Batteries are only practical for relatively small amounts of energy. How do you store more massive quantities? One way is to use it to lift up water and convert the electrical energy to gravitational potential energy. This is called **pumped storage hydroelectricity**.

The Northfield Mountain pumped storage hydroelectric plant - operated by First Light Power Resources - is located in Northfield, MA about 20 minutes about 20 minutes north of campus (up route 63).

The 1080 MegaWatt plant at Northfield Mountain facility opened in 1972 and was the largest in the world at that time.

During periods of low demand, water is pumped 5.5 miles from the Connecticut river to a 300 acre reservoir, 800 feet above the river, which holds 5.6 billion gallons of water.

In generating mode, water flows downhill through 4 turbine generators at a rate of 20,000 gallons per second.



Possible paper topic

Info from http://en.wikipedia.org/wiki/Northfield_Mountain