

## Introduction

Living organisms must eat to sustain themselves. **Why?**

- ...something to do with “we are what we eat”: we get “**building blocks**” (amino acids)
- ...but also something to do with “calories”: we get “**energy**”

In exploring the **origin of life**, it helps to better understand **what life is**. We will see that **energy**—in particular, the **flow** of energy, and its **dispersion**—is central to this understanding.

But first, and more broadly, the concept of “**energy**” and the principle of “**conservation of energy**” are central to all of science, and so worthwhile to explore.



<http://www.healthyalberta.com/1497.htm>

Conservation of energy, do it bitch.

## Kinetic Energy

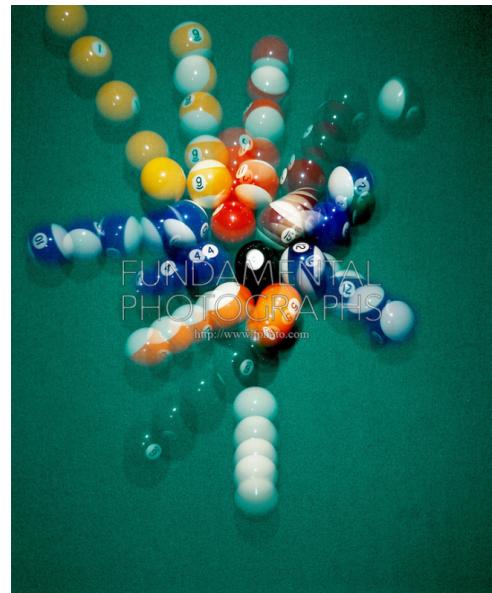
- Beginning with Gottfried Wilhelm Leibniz in the 1670s–80s, people eventually realized that in certain mechanical systems (of several masses moving in this ~~beside~~ direction), quantity

$$\sum \frac{1}{2} m_i v_i^2$$

is **conserved**: it remains *unchanged*, e.g., during “elastic” collisions.

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- He called this quantity **vis viva** (“living force”). Although he didn’t know it, this term is not far off the mark (it’s actually **flow/dispersion** of energy that animates life...)
- Physicists now call this quantity **kinetic energy**: the energy stored in the motion of a mass
- Physicists now call this quantity **kinetic energy**: the energy stored in the *motion* of a mass



2m

m

"Elastischer stoß3" by Raul Roque

For instance, if we use the known equation for kinetic energy ( $\frac{1}{2}mv^2$ ) we can calculate the total energy before a collision and then again after. These two values are equal. Leibniz called this living force ("vis viva").

## Potential Energy

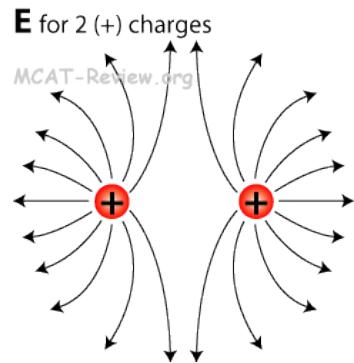
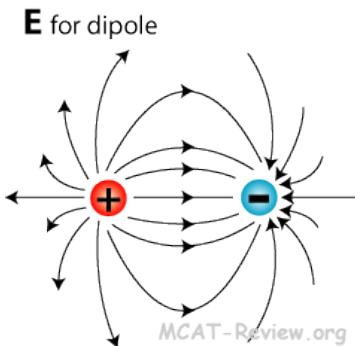
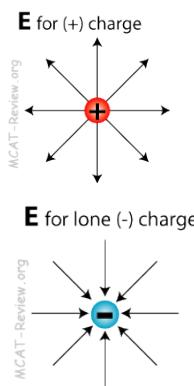
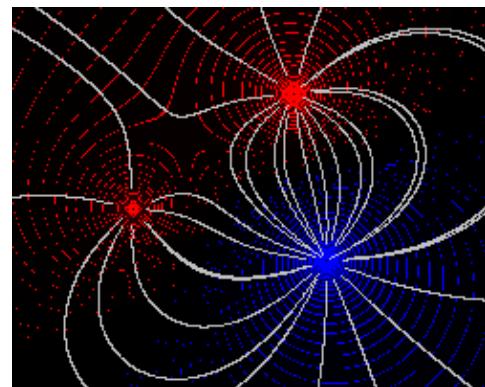
- When a ball collides “elastically” with a wall, it momentarily comes to rest, and so has no kinetic energy
- However, it’s **shape is distorted**. Like a compressed spring, it “springs back” to its original shape and restores the ball’s original kinetic energy
- We sometimes say that the distorted ball stores “elastic potential energy”, but it’s really energy stored in an atomic-scale **electric field** inside the ball



Energy can be converted to different types. For instance, when we throw a ball at a wall it is moving towards the wall, but it eventually slows to a stop. The kinetic energy that it had is used to distort the shape of the ball converting the energy into elastic potential energy. This is energy stored in the electric field in the ball.

## Potential Energy

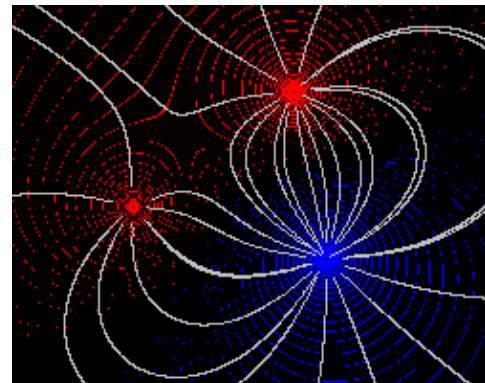
- Atoms are made of electrically charged particles: a positively-charged nucleus and negatively-charged electrons
- Each charged particle is surrounded by an electric field,  $\mathbf{E}$
- The electric fields of two or more charged particles add to produce a net electric field in the space around the particles



All atoms have positively and negatively charged particles in them. In the area around these particles there are electric fields

## Potential Energy

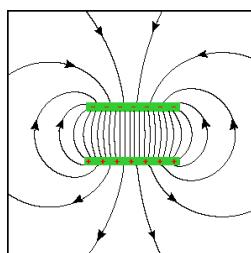
- An electric field stores energy in the space between charged particles, with energy density  $\frac{1}{2} |E|^2$  (joules per cubic meter)
- Distorting the shape of an elastic ball distorts the atomic-scale electric field, changing the energy stored in the field
- As the ball is coming to rest, the distortion increases the energy stored in the electric field, at the expense of decreasing the energy stored in the motion of its mass
- As the ball springs back, the reverse happens: electric field energy is converted back into kinetic energy
- But the **total** energy (kinetic + potential) is **conserved** (constant)



The electric field stores energy in the space between charged particles. The equation for this is  $\frac{1}{2}|E|^2$ . When the ball distorts in shape the kinetic energy is stored in this field (since the area is warped).

## Potential Energy

The **electric field energy** stored between two metal plates...



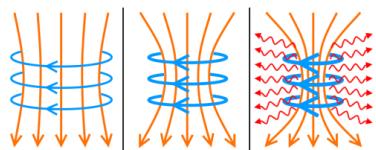
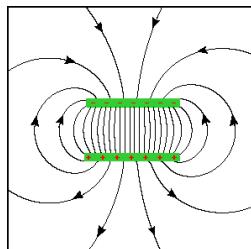
...can be converted into **kinetic energy** (in this case a 3.2 kg projectile moving at Mach 7)



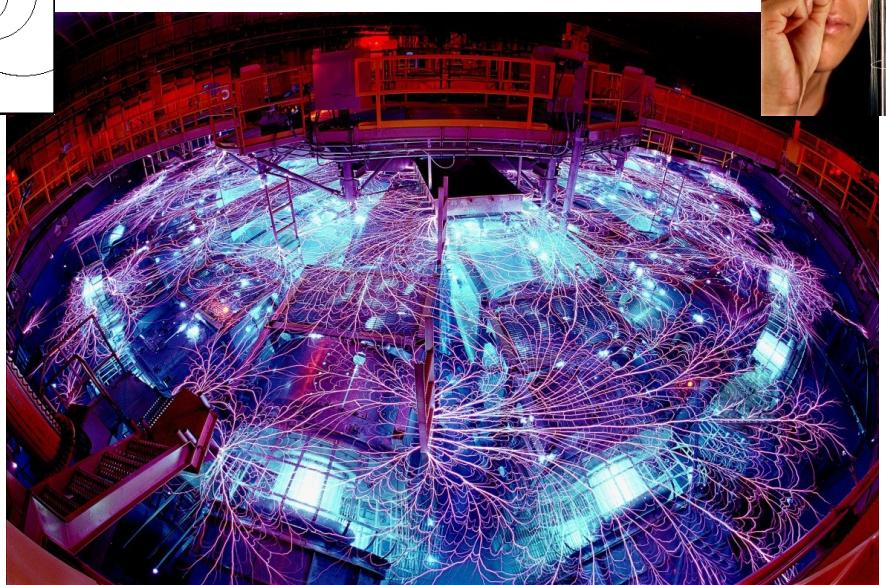
When you create a difference in charges between two plates. By putting a piece of metal between the two pieces it shorts out the fields which converts it all into kinetic energy which propels the metal really fast. It also creates plasma due to the fast amounts of energy being created.

## Potential Energy

The electric field energy stored between two metal plates...



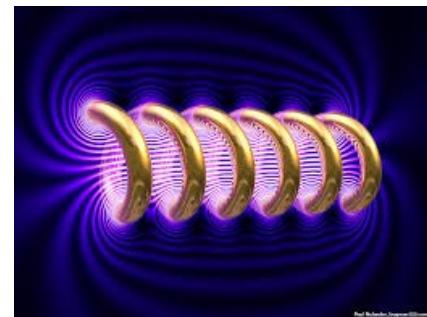
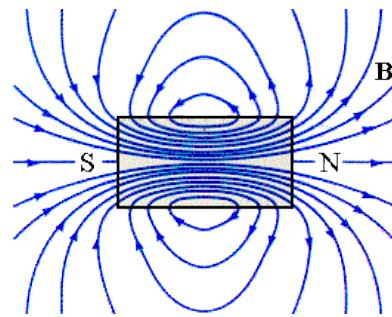
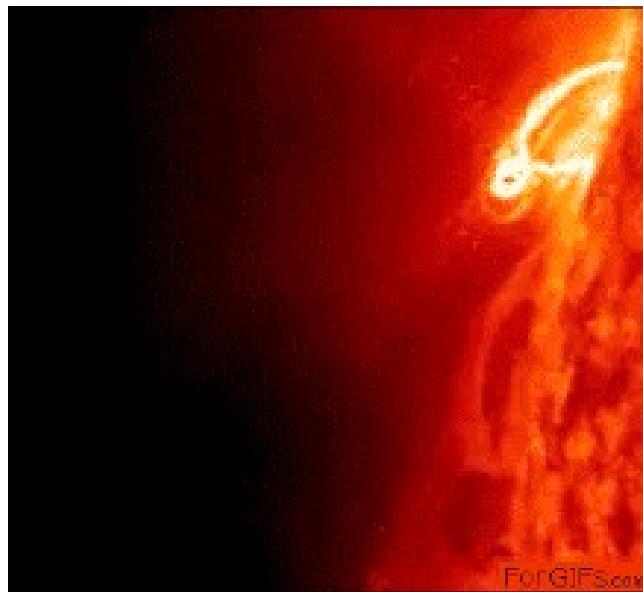
...may spark the release of more energy (via nuclear fusion) through the “Z-pinch” effect (Z-Machine at Sandia National Labs)



We can use these fields to fuse particles by using the kinetic energy from a conversion from electric potential energy to squish things.

## Potential Energy

- Energy can also be stored in a **magnetic field**,  $B$  (with energy density (joules per  $\frac{1}{2} \text{ amp}^2 \text{ meter}^2$  per cubic meter))



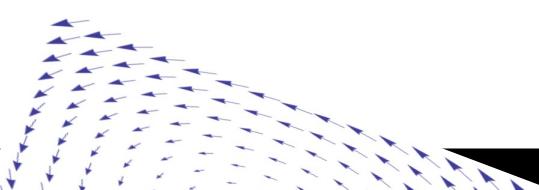
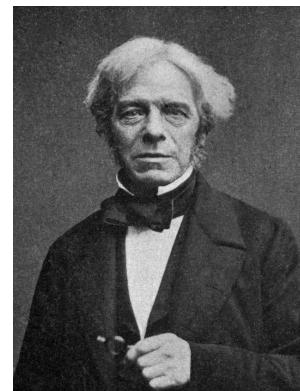
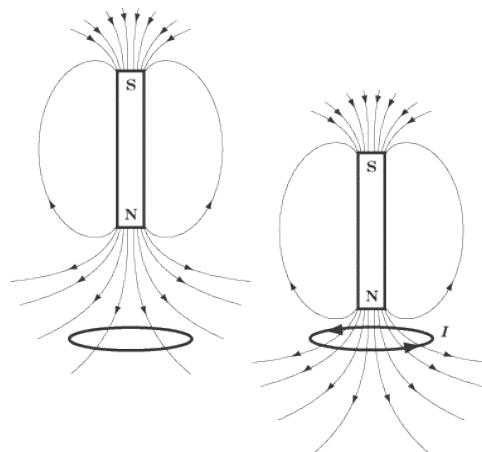
A solar flare converts magnetic field energy into kinetic energy (up to  $10^{25}$  billions of times the most powerful nuclear bombs humans have built)

Energy can also be stored in a magnetic field  $\frac{1}{2}|B|^2$ . A solar flare is when the energy stored in these magnetic fields is released by the field breaking.

## Potential Energy

- Light is an **electromagnetic field**:

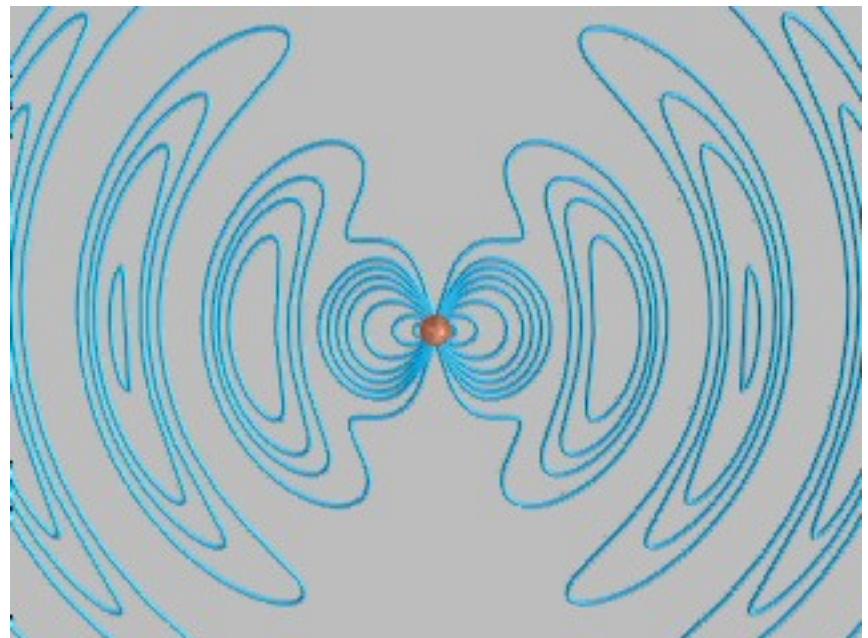
- ✓ **Faraday:** A changing magnetic field creates an **electric field**
- ✓ **Maxwell:** A changing electric field creates a **magnetic field**
- ✓ These two mechanisms work together to create light: a mutually self-sustaining, changing pattern of electric and magnetic fields in space, moving at speed  $c$  (speed of light)



## Potential Energy

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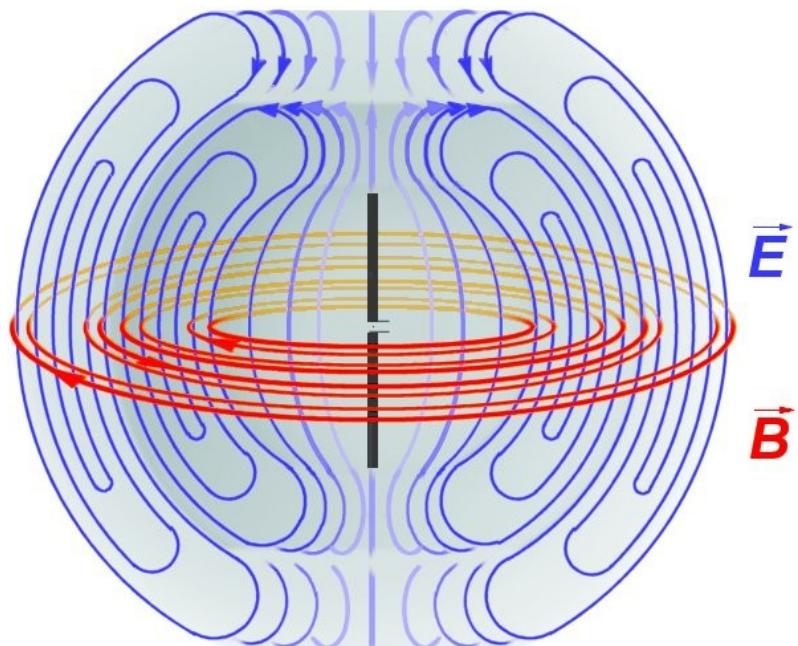


Light is electric and magnetic fields working together. Faraday found a changing magnetic field in space will created an electric field and vice versa. Maxwell is the dude that found the reverse.

## Potential Energy

- Light is an **electromagnetic field**:

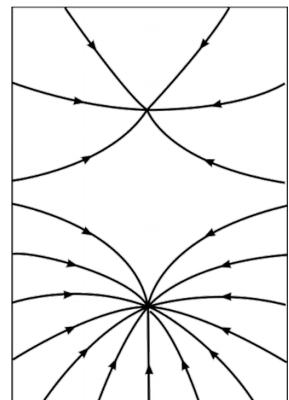
- ✓ **Faraday:** A changing magnetic field creates an **electric field**
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- ✓ These two mechanisms work together to create **light**: a mutually self-sustaining, changing pattern of electric and magnetic fields in space, moving at speed  $c$  (speed of light)



Light is potential energy stored in electric and magnetic fields.

## Potential Energy

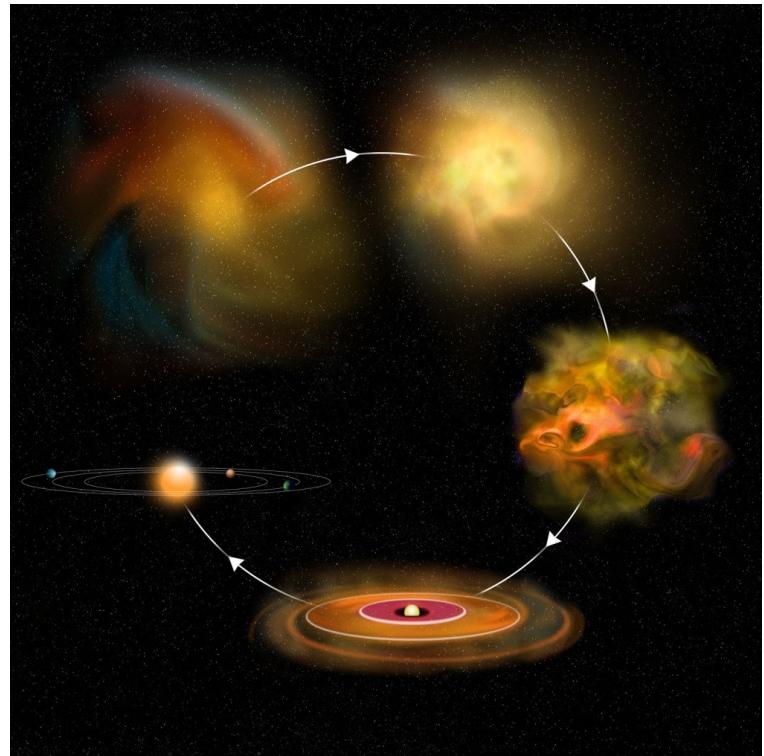
- Energy can also be stored in a **gravitational field**
- When we toss a ball up, it begins with kinetic energy. But at the top of its trajectory the ball is momentarily at rest and has no kinetic energy
- The kinetic energy has been converted into “gravitational potential energy”, which is really energy stored in the **gravitational field** of the two masses (Earth and ball)
- This gravitational field energy is converted back into kinetic energy as the ball falls back down
- But the **total** energy (kinetic + potential) is **conserved**



Energy can be stored in a gravitational field. For instance when you throw something up it slows down because its kinetic energy is being converted into gravitational potential energy which is stored in the gravitational field.

## Potential Energy

Gravitational field energy provided the spark that ignited the Sun's thermonuclear fusion reactions, which now provide virtually all the energy for life on Earth



Solar systems are formed when a giant ball of helium and hydrogen collapses due to gravity. This results in gravitational potential converting into kinetic energy. This kinetic energy becomes thermal energy as particles collide. Eventually this becomes fusion.

## Thermal Energy

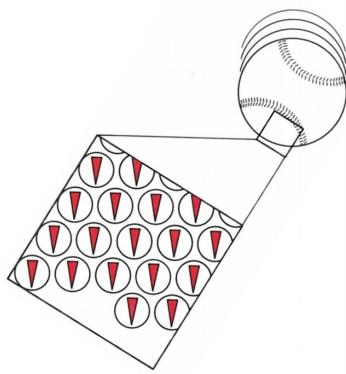
- When a ball bounces elastically, the energy converts back and forth between kinetic and potential (gravitational & electric field) energy, with the **total energy being conserved**
- But when the bounce is *inelastic*, it *seems* as if energy is disappearing...



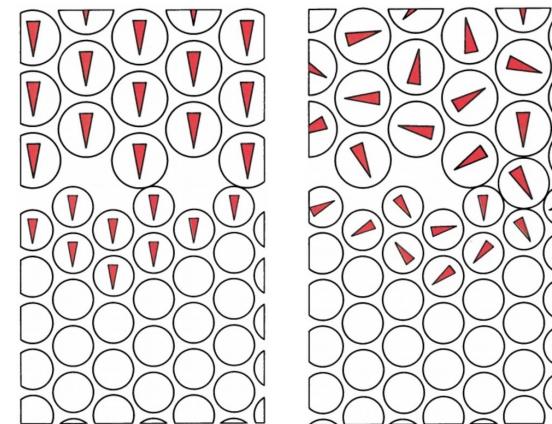
Imagine a bouncy ball bouncing. You get gravitational energy to kinetic energy to elastic energy and back. But you see that the ball is not bouncing as high each time. So where is the energy going.

## Thermal Energy

- Let's focus on what the **collisions** with the ground are doing to the **kinetic energy**:



Ball initially falling



Collisions randomize the kinetic energy

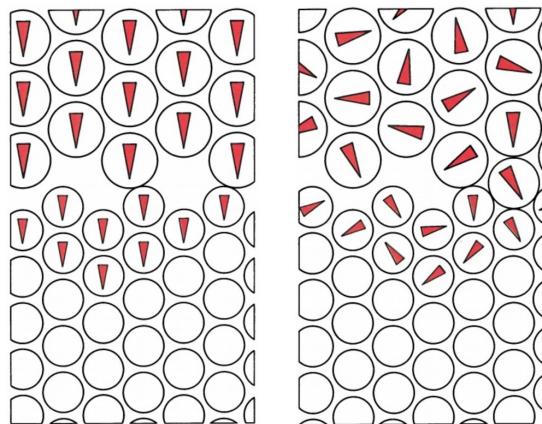
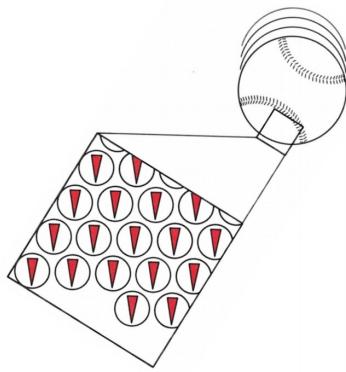


### Initially:

- All the particles in the ball are moving in the same direction
- We say their KE is *coherent* or *ordered*

## Thermal Energy

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Ball initially falling

Collisions randomize the kinetic energy



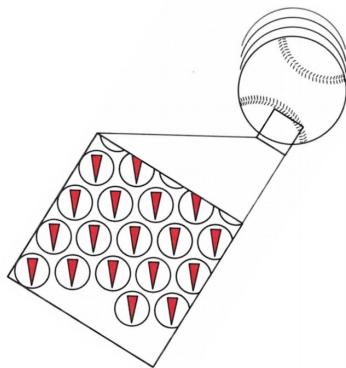
### Each collision:

- Increases the disordered KE of the particles in the ground*
- Decreases the ordered KE of the particles in the ball*

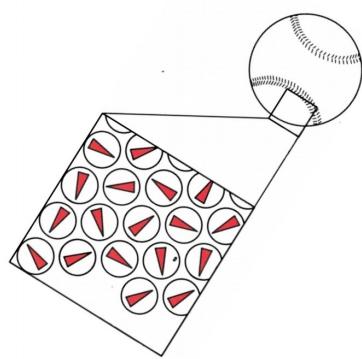


## Thermal Energy

- Let's focus on what the **collisions** with the ground are doing to the **kinetic energy**:



Ball initially falling



Ball finally at rest

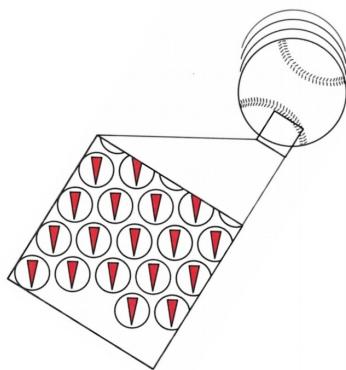
### Finally:

- The particles in the ball have no more *ordered* KE (the ball *as a whole* has no motion)
- The particles in the ground near the ball have acquired more *disordered* KE

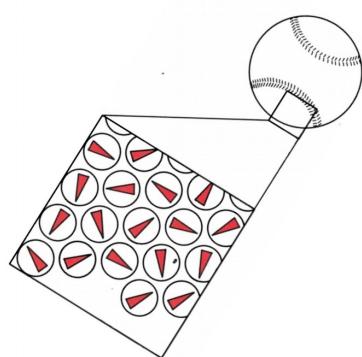


## Thermal Energy

- Let's focus on what the **collisions** with the ground are doing to the **kinetic energy**:



Ball initially falling



Ball finally at rest

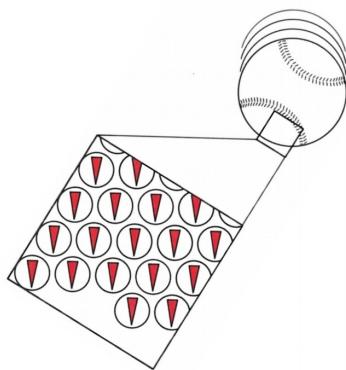
### Finally:

- Also: the ball and the ground near the ball are **warmer**
- Incoherent or disordered KE* is called **thermal energy**: the energy stored in the random “thermal motions” of an object’s particles

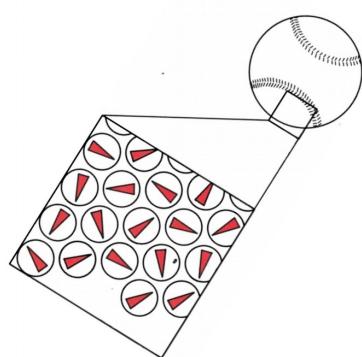


## Thermal Energy

- Let's focus on what the **collisions** with the ground are doing to the **kinetic energy**:



Ball initially falling



Ball finally at rest

### Net result:

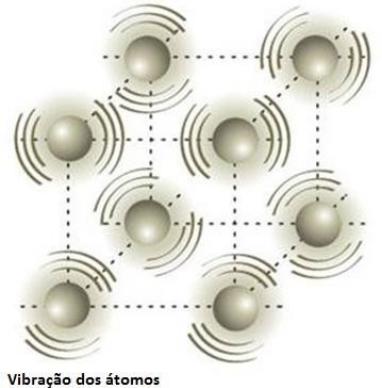
- The collisions have converted kinetic energy into thermal energy
- The **total** energy (ordered + disordered KE) is **conserved**

Before the ball hits the table all atoms in it have the same velocity. When it hits the table the atoms in the ball hit the atoms in the table transferring kinetic energy in random directions. Now we have disordered kinetic energy. This disordered kinetic energy comes from ordered kinetic energy (the energy we see when the ball bounces) which results in the lower bounces.

Life uses this disordered kinetic energy to do stuff. Disordered kinetic energy is called thermal energy. Life want to covert disordered kinetic energy into ordered kinetic energy.

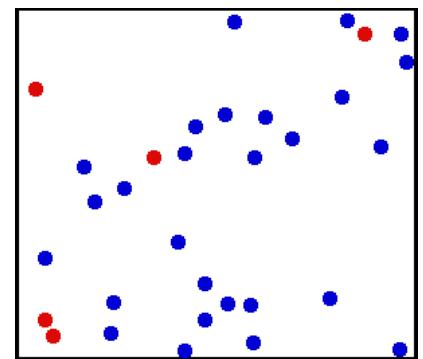
## Thermal Energy

- More correctly: **Thermal energy** is the *total* energy associated with the thermal motion of a system of particles, including both kinetic and potential (field) energies



Vibração dos átomos

- In the case of a gas, the potential (field) energies are negligible, and the thermal energy is in the form of the disordered kinetic energy of the gas particles

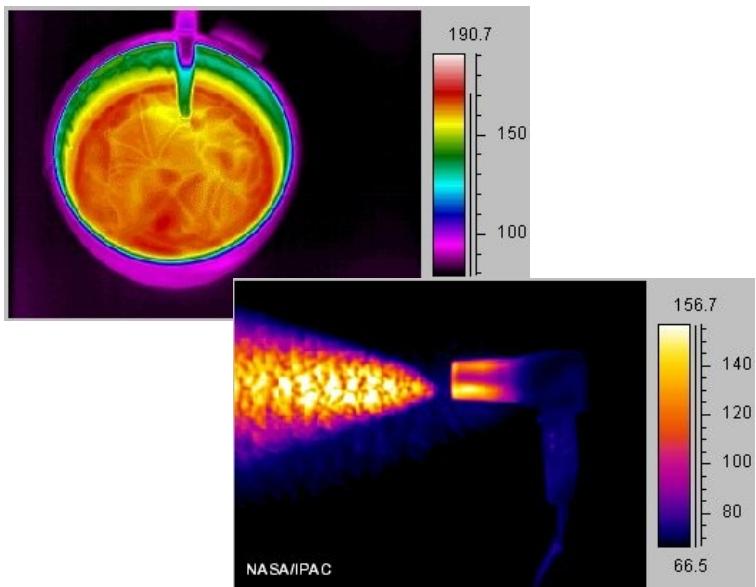


"Translational motion" by Greg L

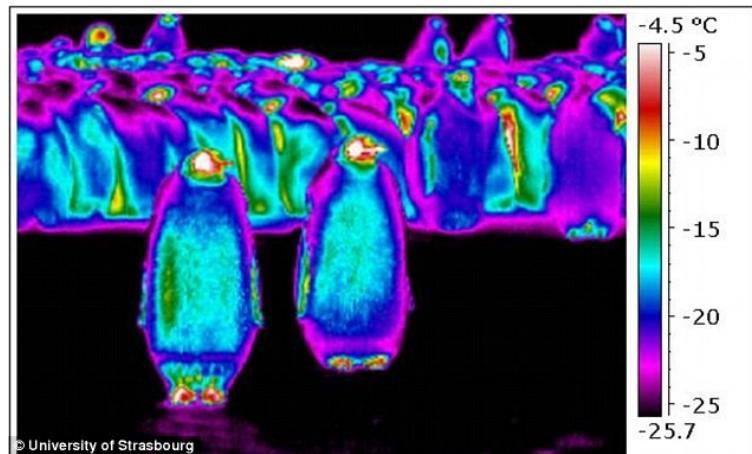
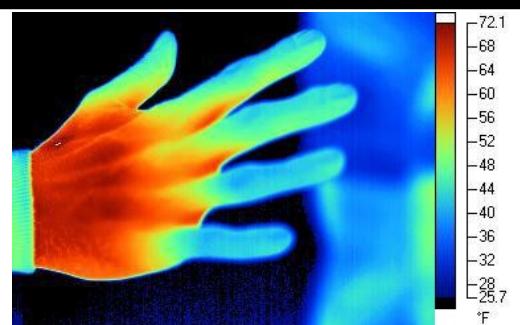
Any item above absolute zero has its items jiggling around (thermal energy).

## Thermal Energy

- All objects store energy in the form of thermal energy
- The **hotter** a given object, the more **thermal energy** it has



NASA/IPAC

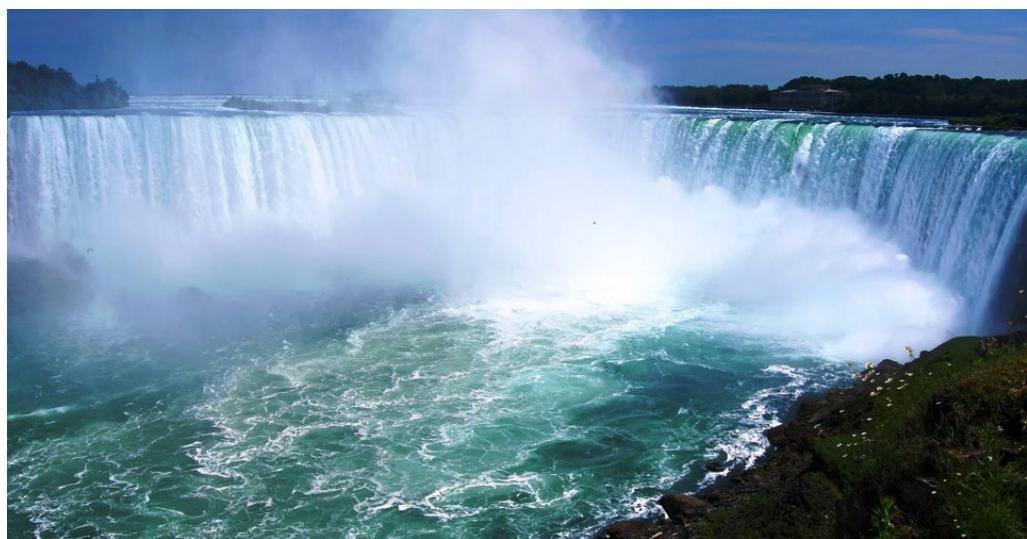


All objects store energy in the form of thermal energy.

## What is Energy?

### Summary:

- Energy is **conserved**. It can flow from place to place, or change its form, but it can never be created or destroyed.



## What is Energy?

### Summary:

- Energy is **conserved**. It can flow from place to place, or change its form, but it can never be created or destroyed.
- The two basic *forms* are:
  - ✓ Kinetic energy (energy stored in the motion of mass)
  - ✓ Potential energy (energy stored in fields: electric, magnetic, and gravitational)

### But what *is* energy?

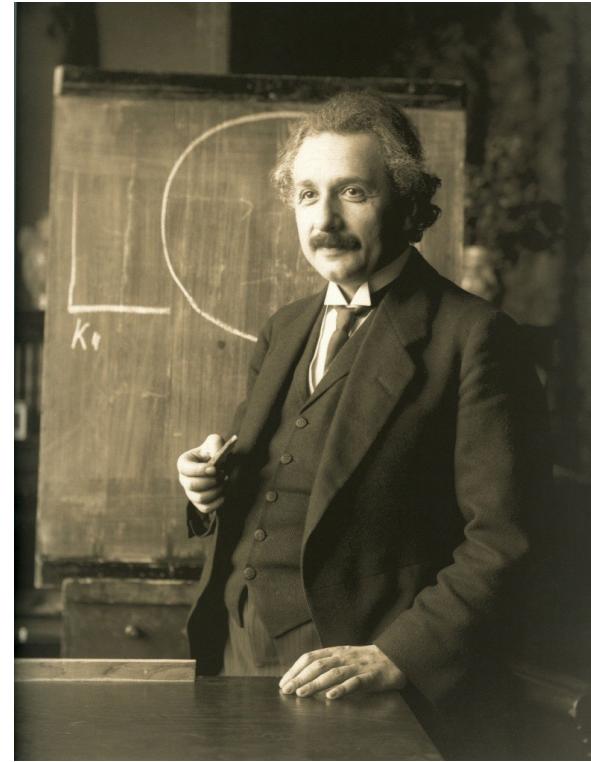
- No one knows. **Energy is a mystery as deep as the universe itself.**
- **Albert Einstein** peered most deeply into this mystery...

## Einstein on Energy

$$E = mc^2$$

...means energy is equivalent to mass

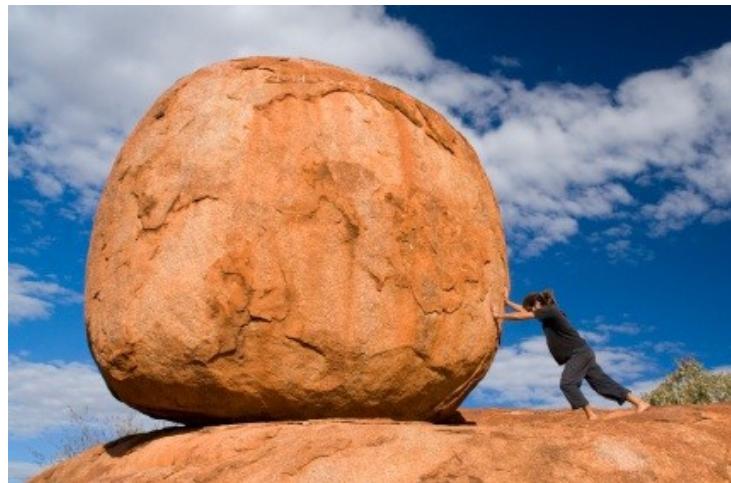
We're not sure what either is, but at least  
the mysteries were reduced from 2 to 1!



Einstein proved that energy is equivalent to mass. The classic  $E = mc^2$ . He also found that space and time are unified.

What does  $E=mc^2$  mean?

**Mass:** the **resistance** of an object to **changes** in its motion  
(another name for mass is *inertia*)



Mass is the resistance of an object to changes in its motion, from here we also get the word inertia.

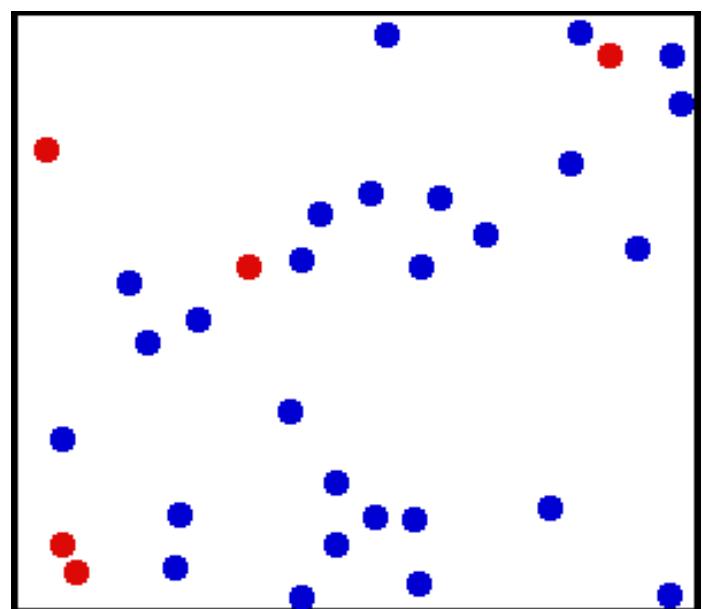
What does  $E = mc^2$  mean?

All forms of energy have mass (or inertia: resistance to acceleration)

Kinetic energy has mass:

Heating the gas in a box (adding KE to the particles) makes it harder to accelerate the box:  $\Delta m = \Delta E/c^2$

It also weighs more



What does  $E=mc^2$  mean?

All forms of energy have mass (or inertia: resistance to acceleration)

Potential energy has mass:

Compressing a spring (adding potential energy to the atomic-scale electric field inside) makes it harder to accelerate the spring:  $\Delta m = \Delta E/c^2$

It also weighs more



What does  $E=mc^2$  mean?

All forms of energy have mass (or inertia: resistance to acceleration)

Thermal energy has mass:

A hot cup of coffee (with more kinetic and potential energy) is harder to accelerate than a cold cup (with the same number of molecules):  $\Delta m = \Delta E / c^2$

It also weighs more



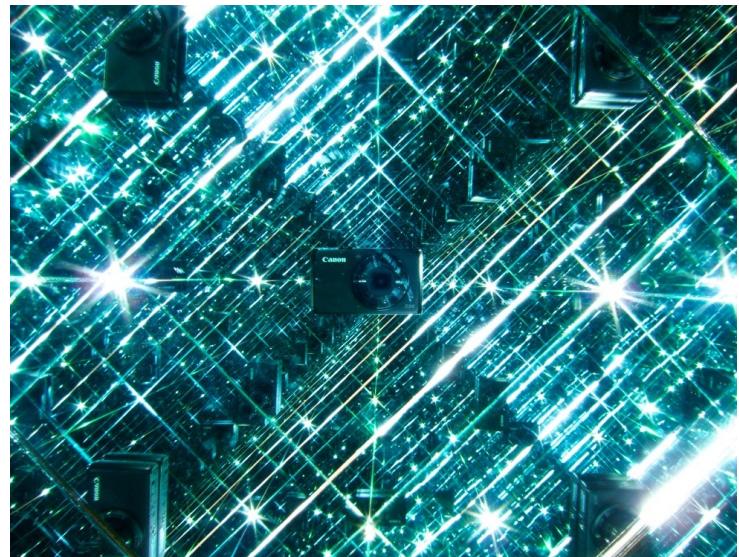
What does  $E=mc^2$  mean?

All forms of energy have mass (or inertia: resistance to acceleration)

**Electromagnetic energy has mass:**

A mirror box full of light is harder to accelerate than the same box empty (dark):  $\Delta m = \Delta E/c^2$

It also weighs more

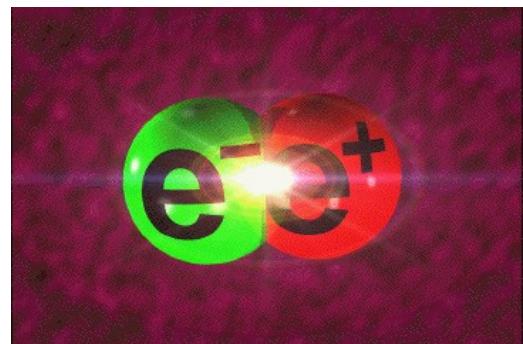


All forms of energy have mass. If we compress a spring, adding more energy, then it becomes harder to accelerate. Its a super small number because you are diving by  $c^2$ . Its hard to detect, but its there. Ditto for thermal energy or electromagnetic energy. If you add light to a box full of mirrors it will be harder to accelerate.

What does  $E=mc^2$  mean?

Turning it around: **mass itself has energy**

- An electron and a positron (the electron's antimatter cousin) both have the same "rest mass". They can annihilate each other, leaving an equivalent amount of mass-energy in the form of light
- The total **mass** does not change. The total **energy** does not change. *Mass is not "converted into energy", or vice versa.* It's just 20<sup>th</sup> century alchemy: one type of matter (electrons) is converted into another (photons)
- "Conservation of energy" and "conservation of mass" are the *same* law, because energy and mass are *equivalent*



Every particle has an anti particle that attract each other. When they collide they become pure energy. The total mass does not change even though the number of particles did. A common misconception is that the mass in the sun is converted into energy. This is not really true since the amount of mass is the same. It just converting between types of particles.

What does  $E=mc^2$  mean?

**So what?**

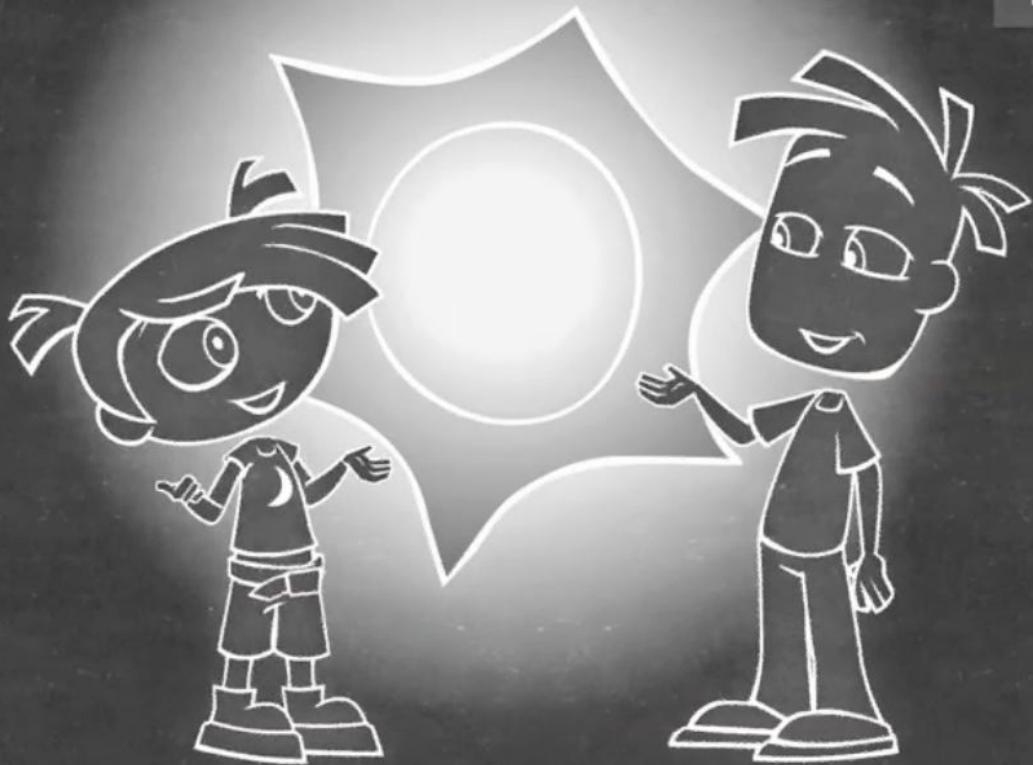
## What does $E=mc^2$ mean?

- The equivalence of energy and mass is a profound insight into the nature of reality.
- E.g., it finally answered the deep mystery of what could possibly be powering the Sun (and other stars): **Fusion**
- ✓ Equivalent to a ~~billion billion~~ large power plants on Earth
- ✓ In each second  $\Delta m = \Delta E/c^2$  = Great Pyramid of Giza
- ✓ Will do this for 10 billion years



**010**

**+205**





What does  $E=mc^2$  mean?

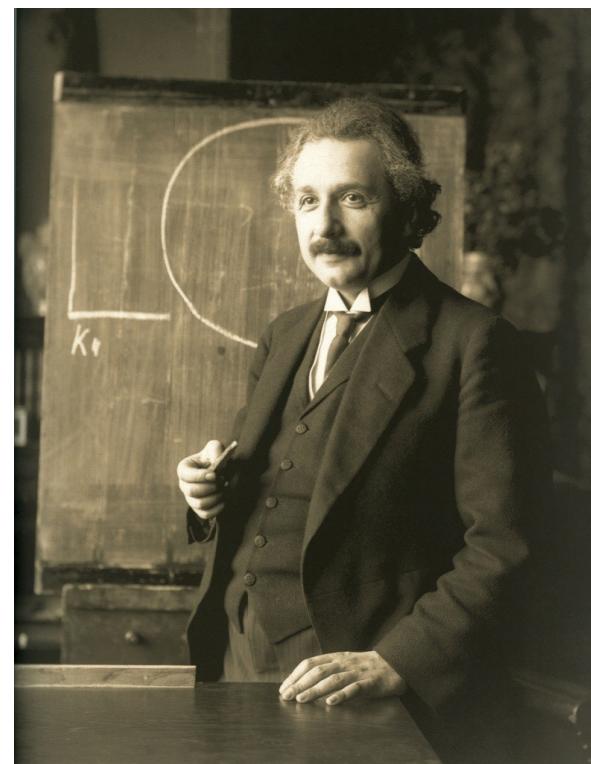
We are *literally* eating the Sun

Life is *profoundly* physical

## Einstein on Energy

**What is energy?** Einstein's first deep insight:

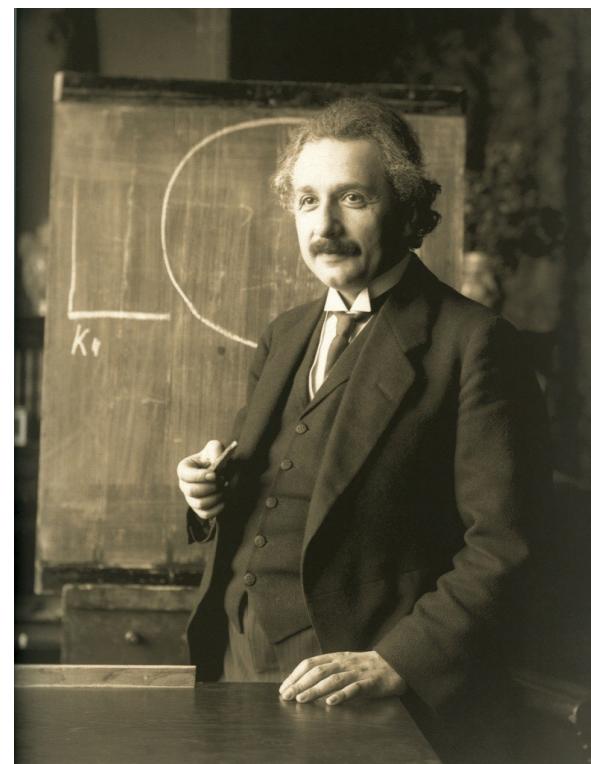
$$\text{energy} = \text{mass}$$



## Einstein on Energy

**What is energy?** Einstein's second, even deeper insight:

**mass-energy = warping of spacetime**



Mass-energy is the same thing as the warping of space time.

## Einstein on Energy



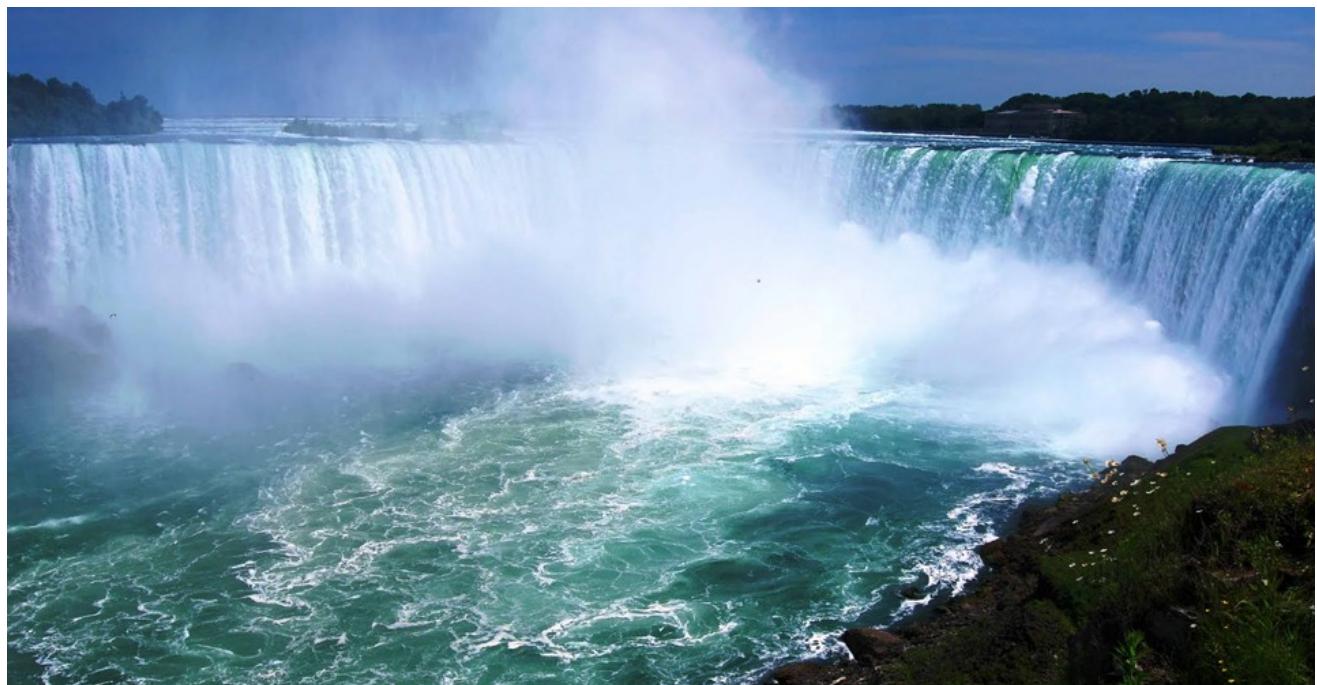
## Einstein on Energy

**Mass-energy is the essence of all things, including life**

**...and it is inextricably woven into the very fabric of  
space and time itself**

...back to energy conservation

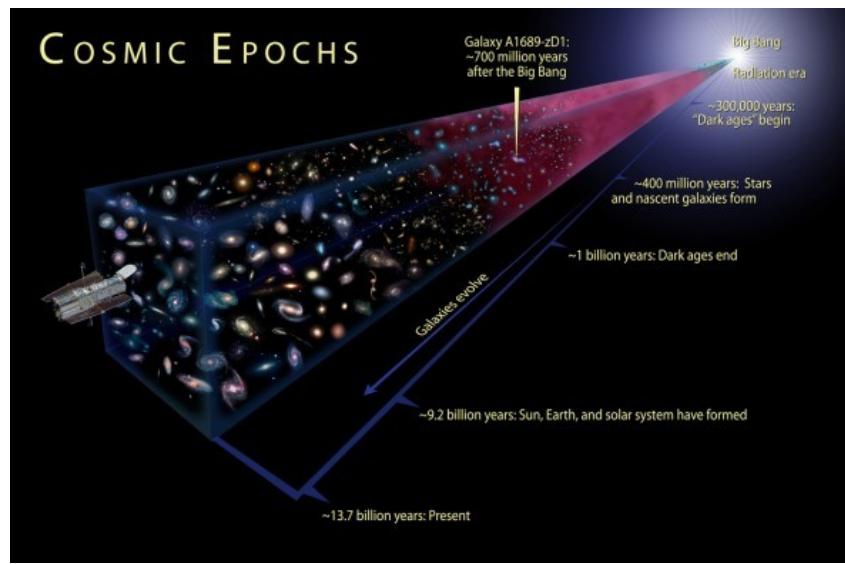
If energy is **strictly conserved** (as it seems to be)...



...back to energy conservation

...then energy is **eternal**.

- **Energy will never run out.** The universe contains the same amount of energy today as it did at the Big Bang.



...back to energy conservation

...then energy is **eternal**.

- We can't "use" energy, or "waste" energy. Energy will **never run out**.



...back to energy conservation

- Energy will never run out, but it “**runs down**.”
  - What’s running out is **useful** energy (called “**free energy**”)



Useful



Useless

...back to energy conservation

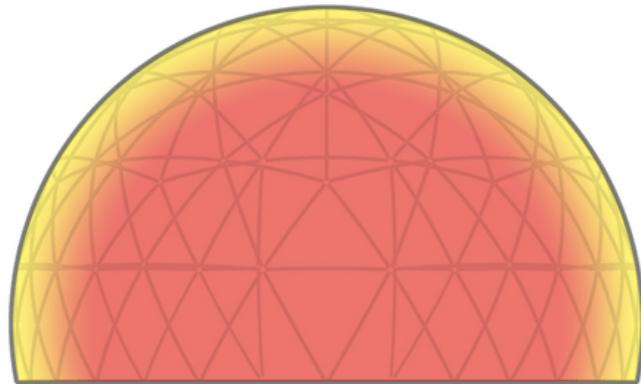
- Energy will never run out, but it “**runs down**.”
  - If the universe were to reach **equilibrium** (no gradients of temperature, pressure, density,...), energy could no longer **flow/transform**. “**Lifeblood**” would “**freeze**.”



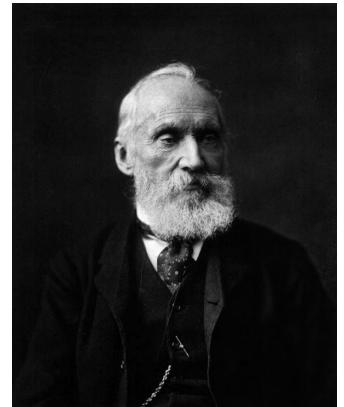
The univery is slowly approaching equilibrium at which point there will be no more flow of energy.

## Heat Death of the Universe...and Life

- When free energy runs out, the universe can no longer sustain processes that use up free energy (like computation or life).
- This possibility (not certain) is called the **heat death of the universe...**



Kelvin  
originated the  
idea of  
universal heat  
death in 1852



The logical end is the heat death of the universe which is the point at which everything is the same temperature.

## Heat Death of the Universe...and Life

- **Energy will never run out.** The universe contains the same amount of energy today as it did at the Big Bang.
- But it “**runs down**”. What’s running out is **useful** energy (“**free energy**”)
- But it is precisely this “running down” that is the “force” that **sustains/animates** life, and likely even **created** life...
- All of this is intimately connected with the concept of **entropy**, and the **second law of thermodynamics**, which we’ll turn to next...

