

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>

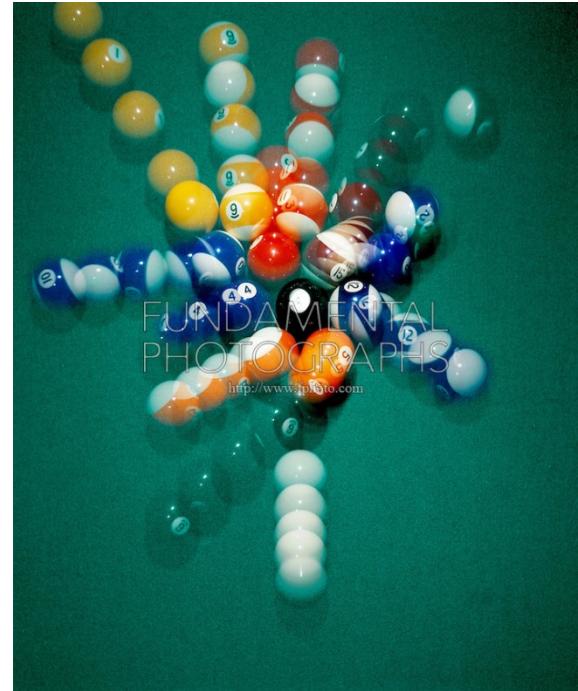
- Beginning with Gottfried Wilhelm Leibniz in the 1670s-80s, people eventually realized that in certain mechanical systems (of several masses moving with it speed), there is a quantity

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

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...)
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- Physicists now call this quantity ***kinetic energy***: the energy stored in the motion of a mass
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2m

m

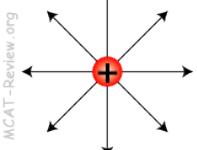
"Elastischer stoß3" by Raul Roque

- 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

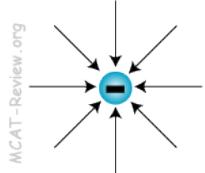


- Atoms are made of electrically charged particles: a positively-charged nucleus and negatively-charged electrons
- Each charged particle is surrounded by an **electric field**, E
- The electric fields of two or more charged particles add to produce a net electric field in the space around the particles

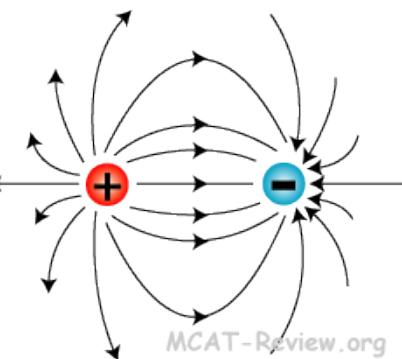
E for (+) charge



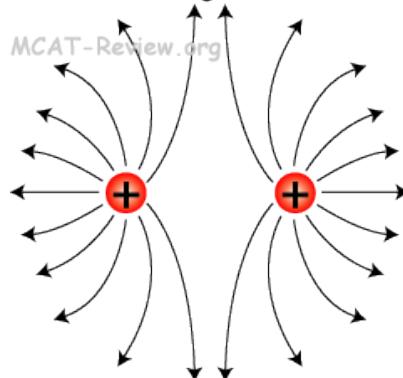
E for lone (-) charge



E for dipole

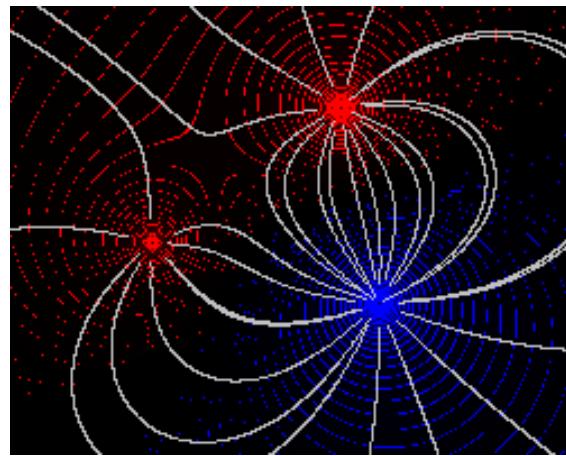


E for 2 (+) charges

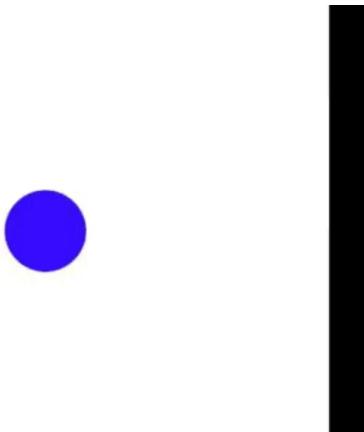
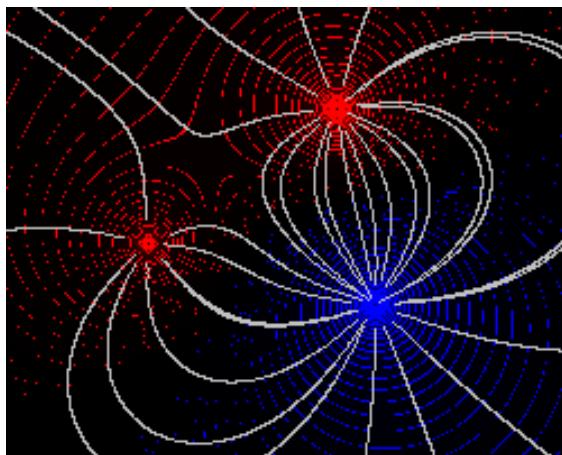


MCAT-Review.org

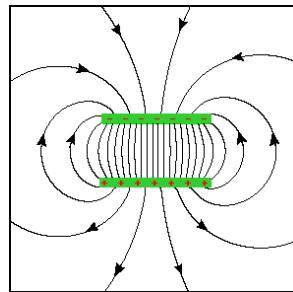
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- An electric field stores energy in the space between charged particles, with energy density $\frac{1}{2} |E|^2$ (joules per cubic meter)
- Distorting the shape of an elastic ball distorts the atomic-scale electric field, changing the energy stored 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)



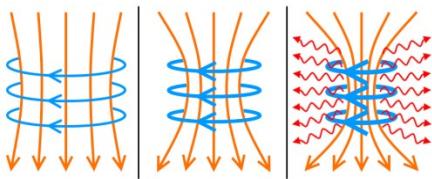
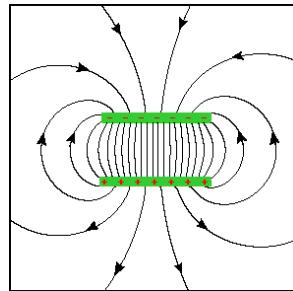
The **electric field energy** stored between two metal plates...



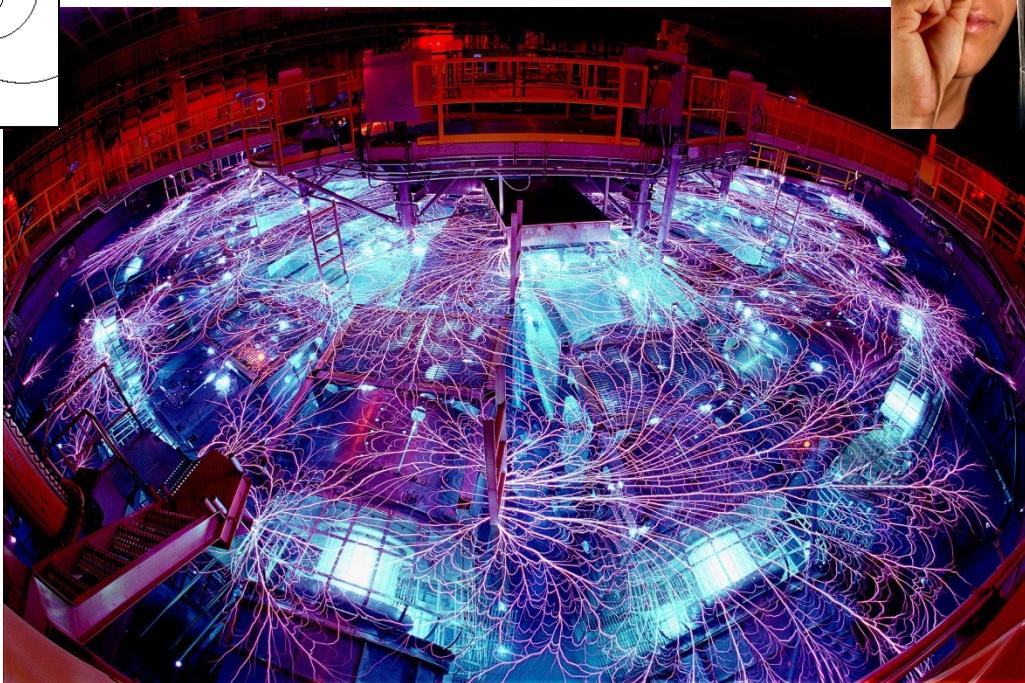
...can be converted into **kinetic energy** (in this case a 3.2 kg projectile moving at Mach 7)



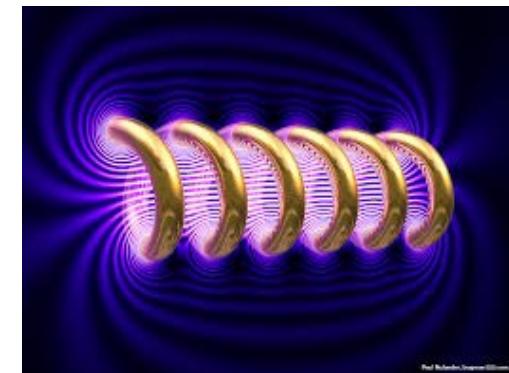
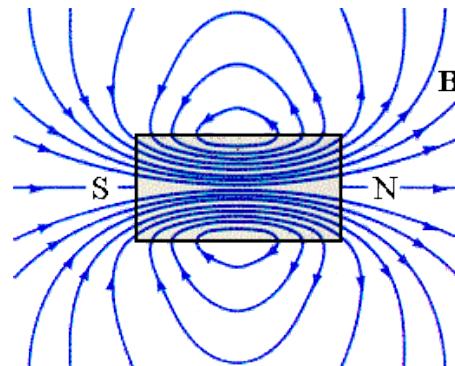
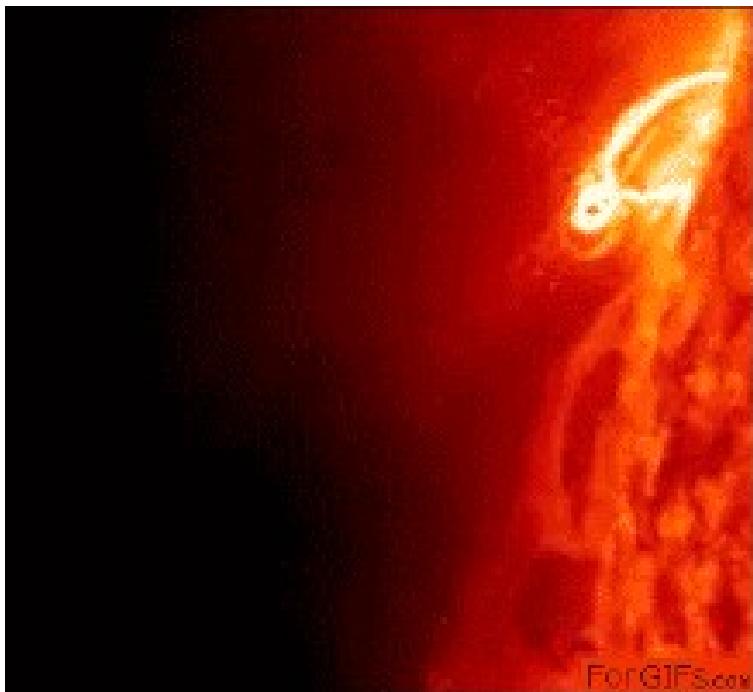
The **electric field energy** stored between two metal plates...



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



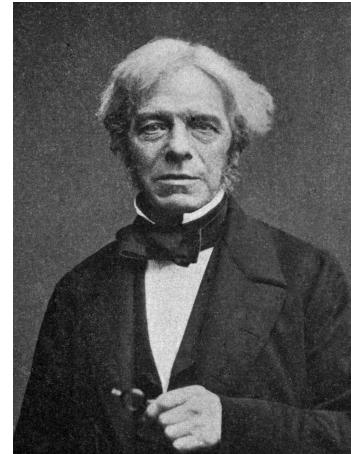
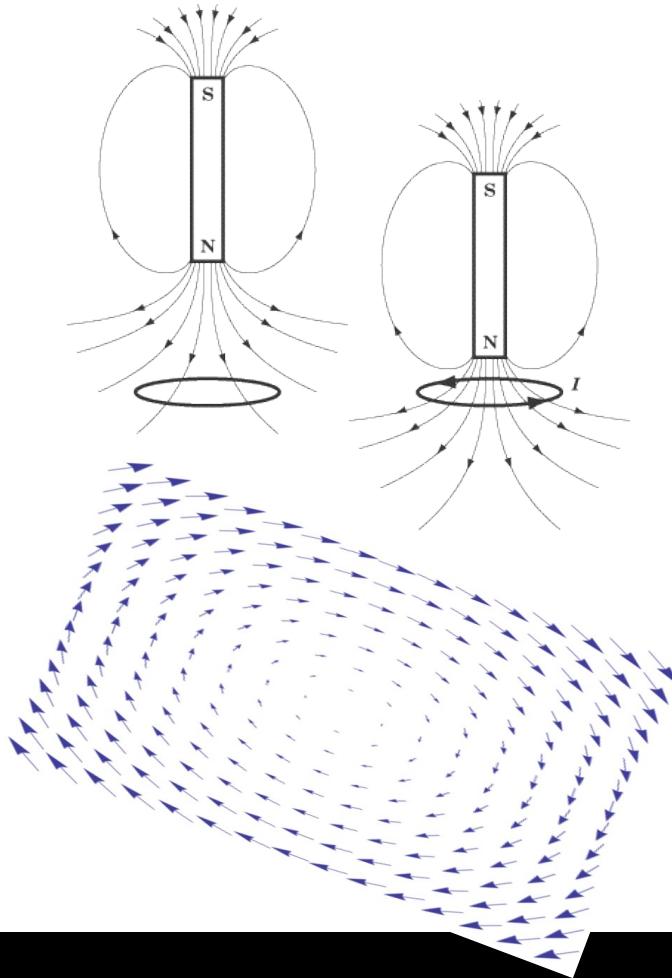
- Energy can also be stored in a **magnetic field**, With energy density (joules per $\frac{1}{2}$ cubic meter) per cubic meter)



A solar flare converts magnetic field energy into kinetic energy (up to 3×10^{25} billions of billions of the most powerful nuclear bombs humans have built)

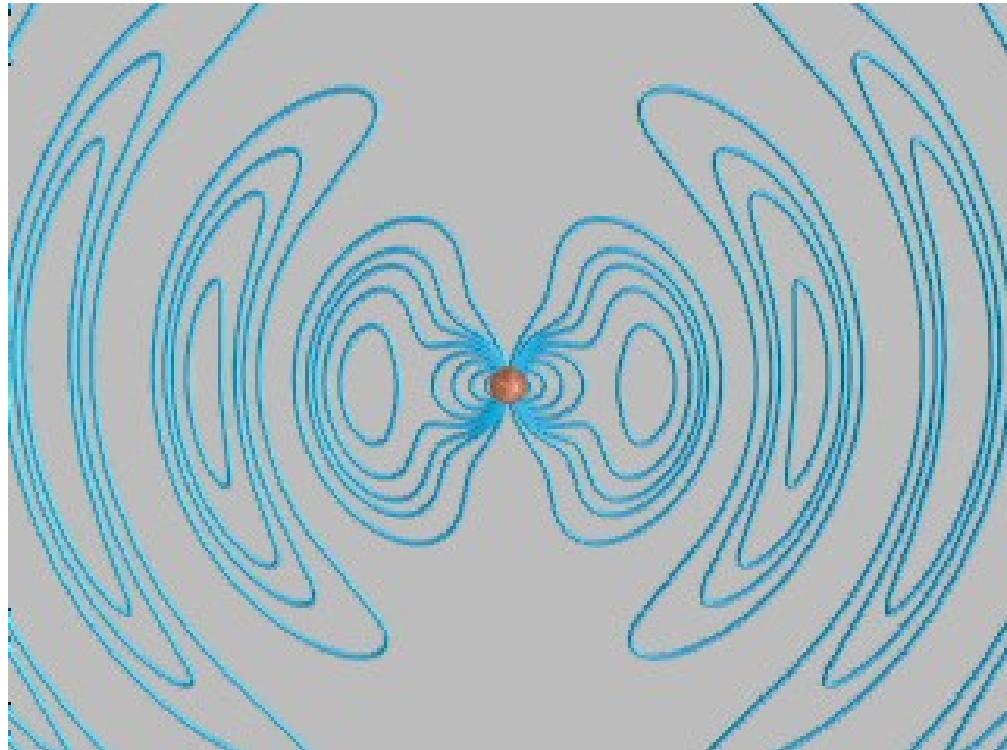
- Light is an **electromagnetic field**:

- ✓ 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)



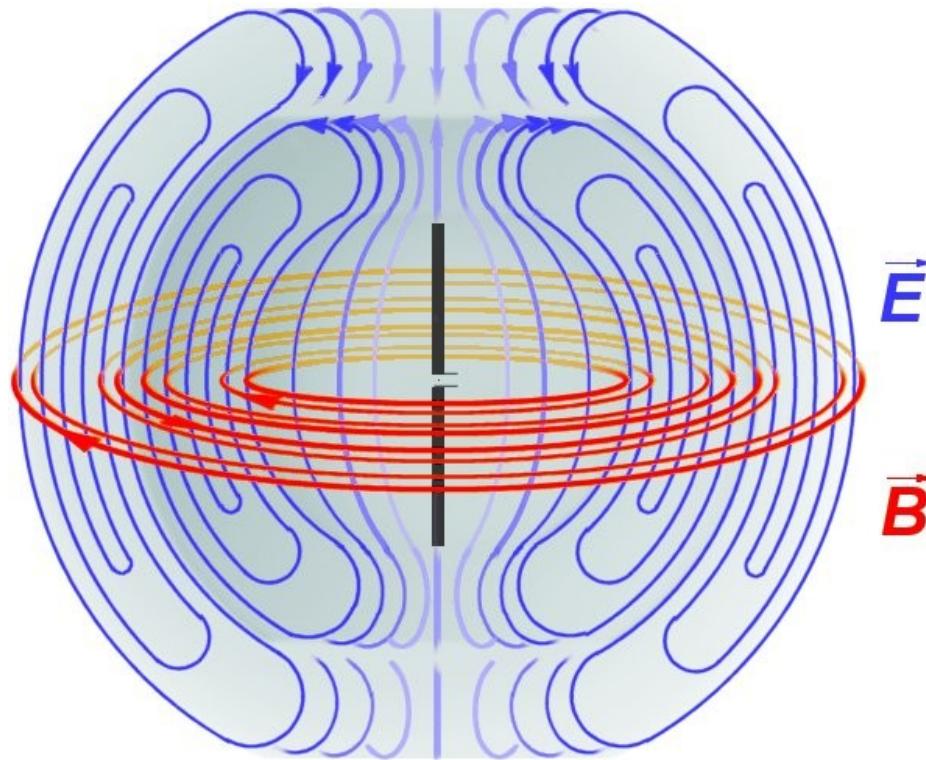
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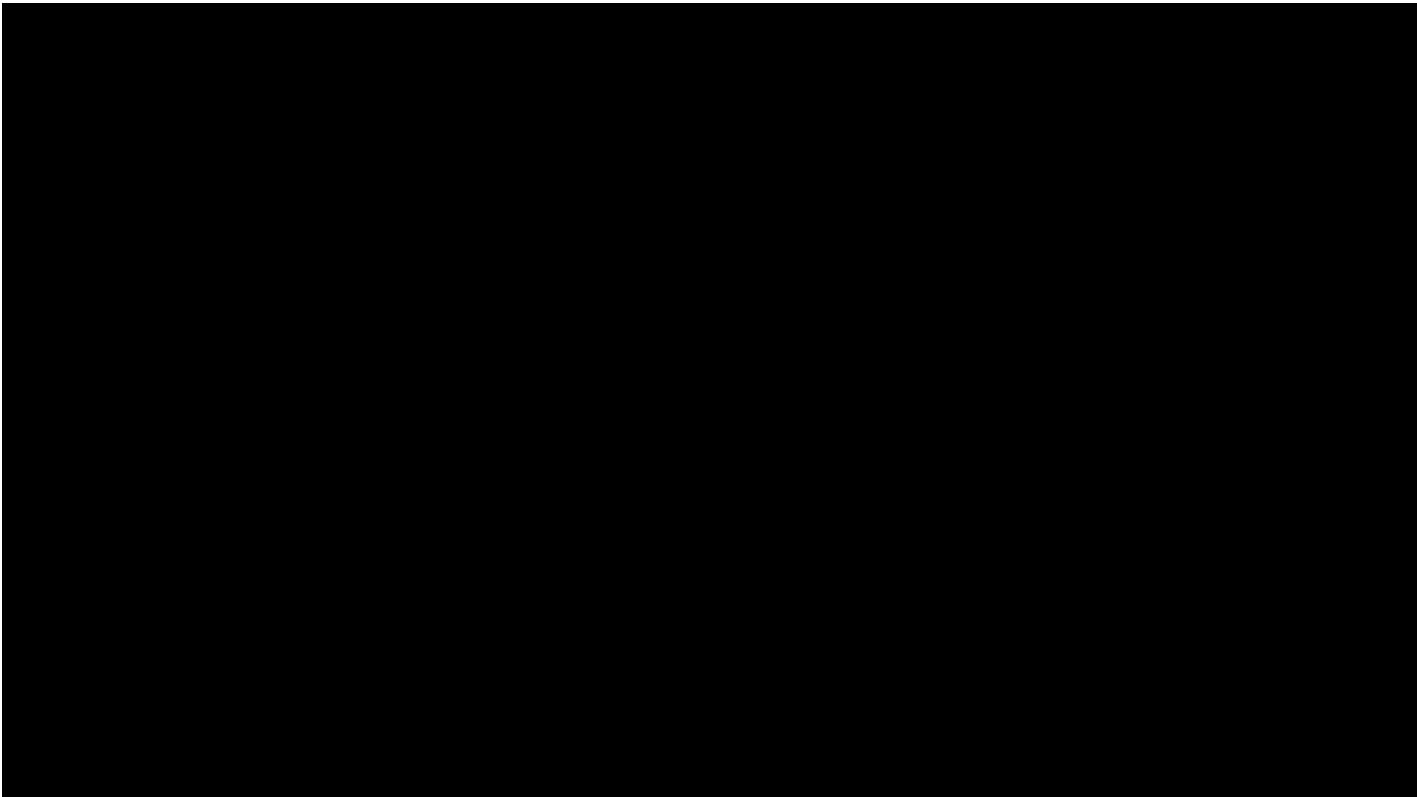
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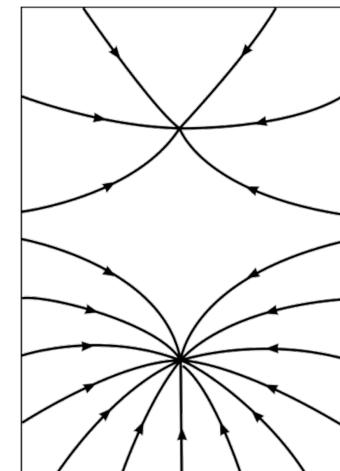
Light is potential energy stored in electric and magnetic fields, being transported through vacuum at 300 thousand km per second



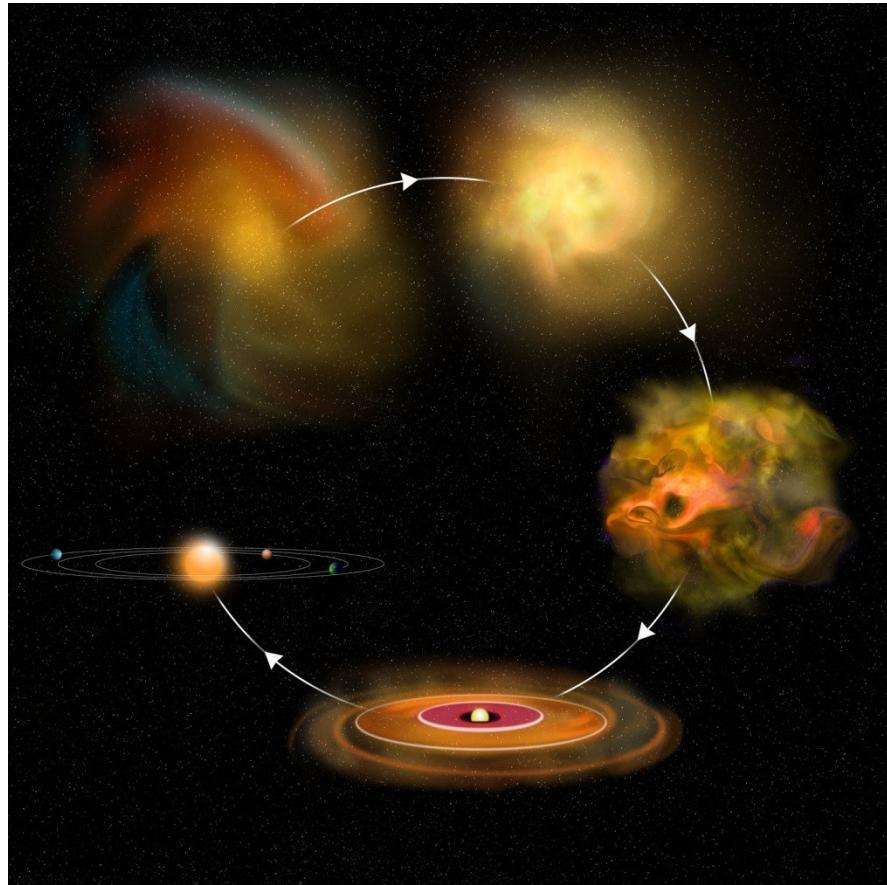
- Energy can also be stored in a **gravitational field**



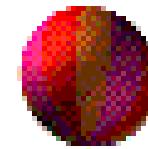
- Energy can also be stored in a **gravitational field**
- When we toss a ball up, it begins with kinetic energy. But at the top of its trajectory the ball is momentarily at rest and has no kinetic energy
- The kinetic energy has been converted into “gravitational potential energy”, which is really energy 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**



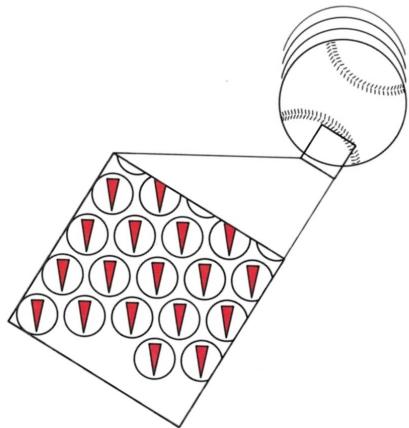
Gravitational field energy provided the spark that ignited the Sun's thermonuclear fusion reactions, which now provide virtually all the energy for life on Earth



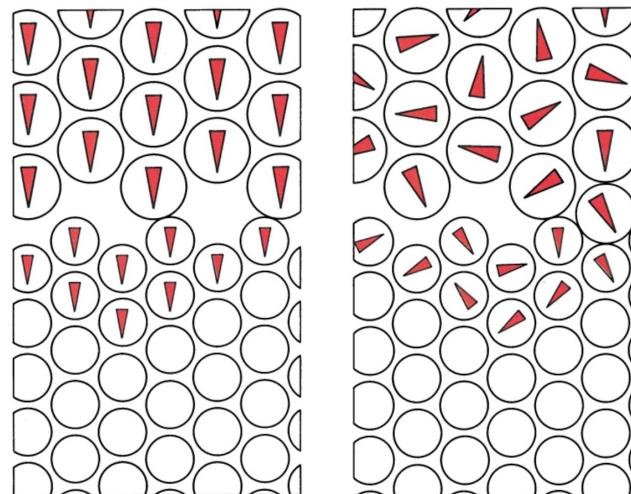
- When a ball bounces elastically, the energy converts back and forth between kinetic and potential (gravitational & electric field) energy, with the **total energy being conserved**
- But when the bounce is *inelastic*, it seems as if energy is disappearing...



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



Ball initially falling



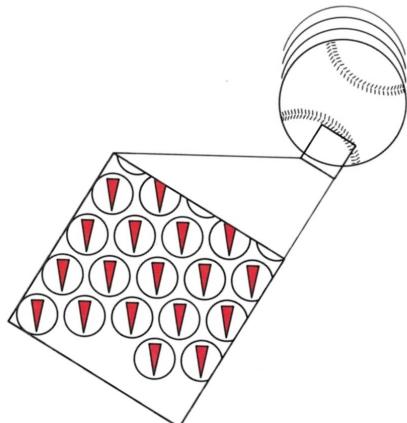
Collisions randomize the kinetic energy

Initially:

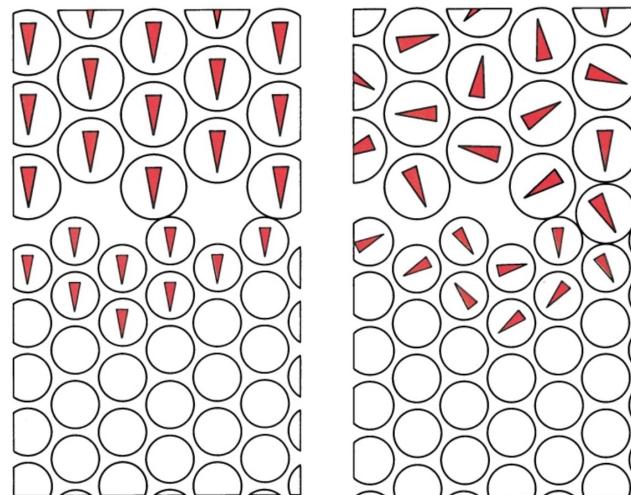
- All the particles in the ball are moving in the same direction
- We say their KE is *coherent* or *ordered*



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



Ball initially falling



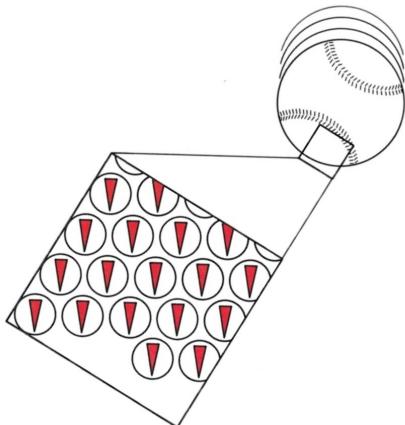
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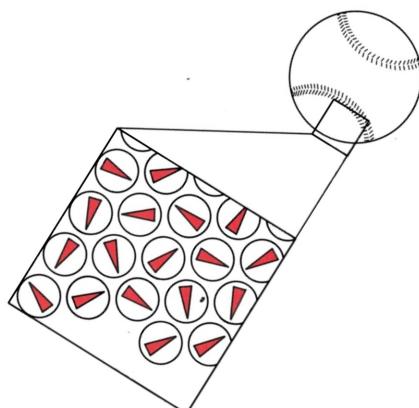
Each collision:

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

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



Ball initially falling

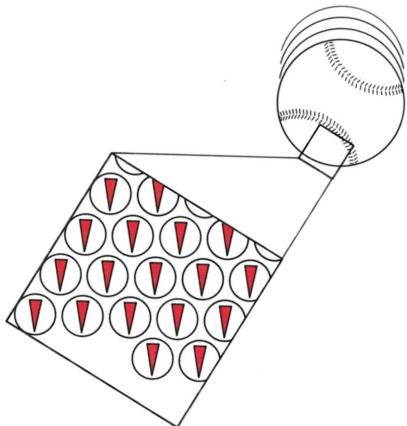


Ball finally at rest

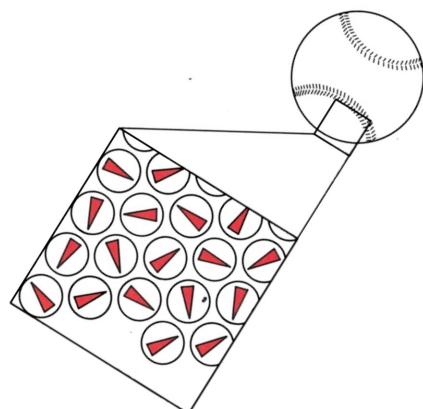
Finally:

- 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*

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



Ball initially falling

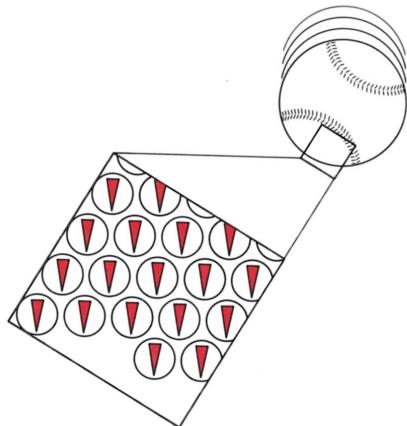


Ball finally at rest

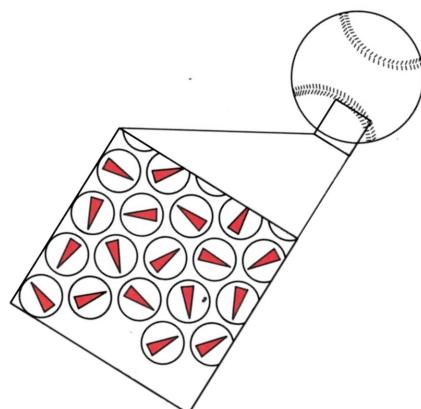
Finally:

- 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

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



Ball initially falling

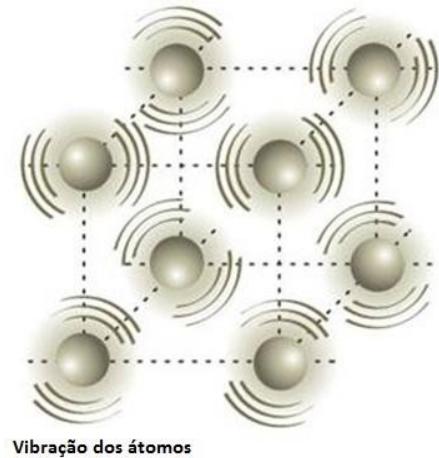


Ball finally at rest

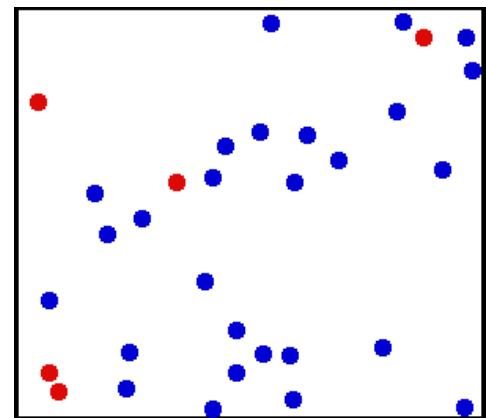
Net result:

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

- 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
- 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

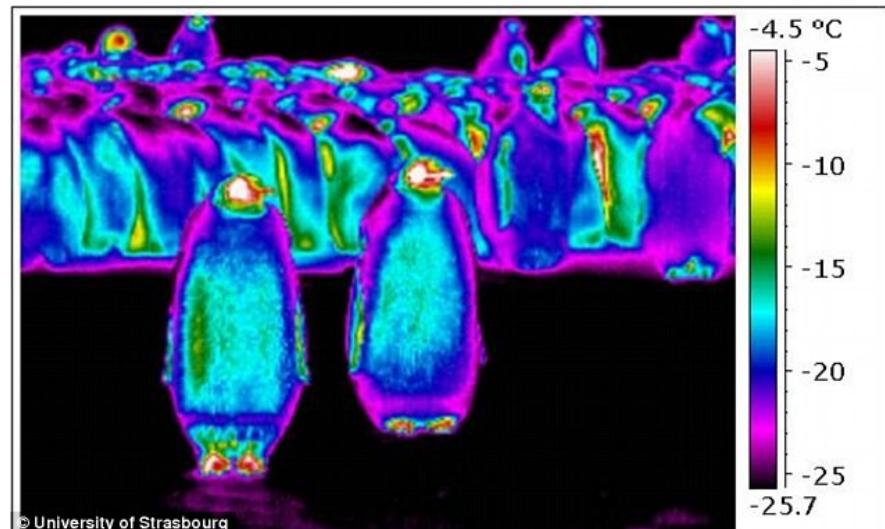
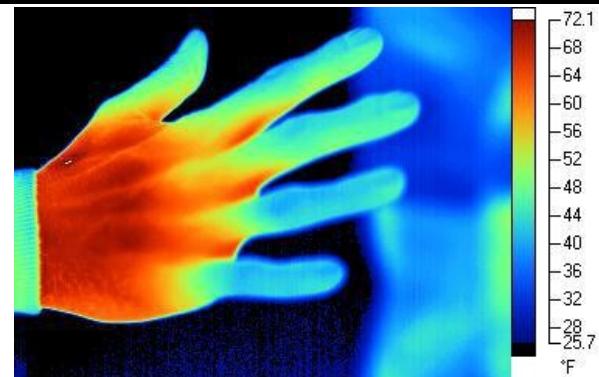
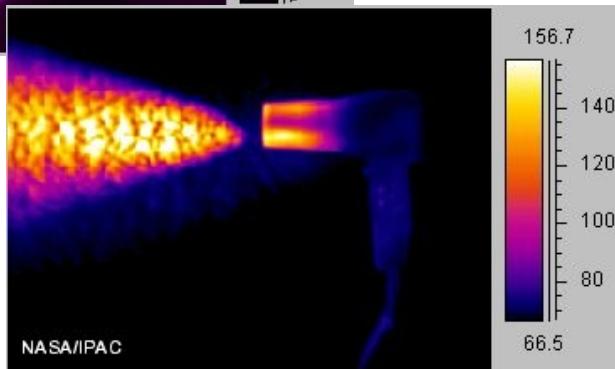
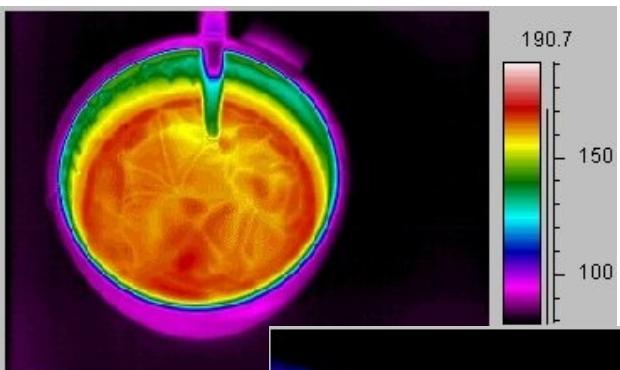


Vibração dos átomos



"Translational motion" by Greg L

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



Summary:

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



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)

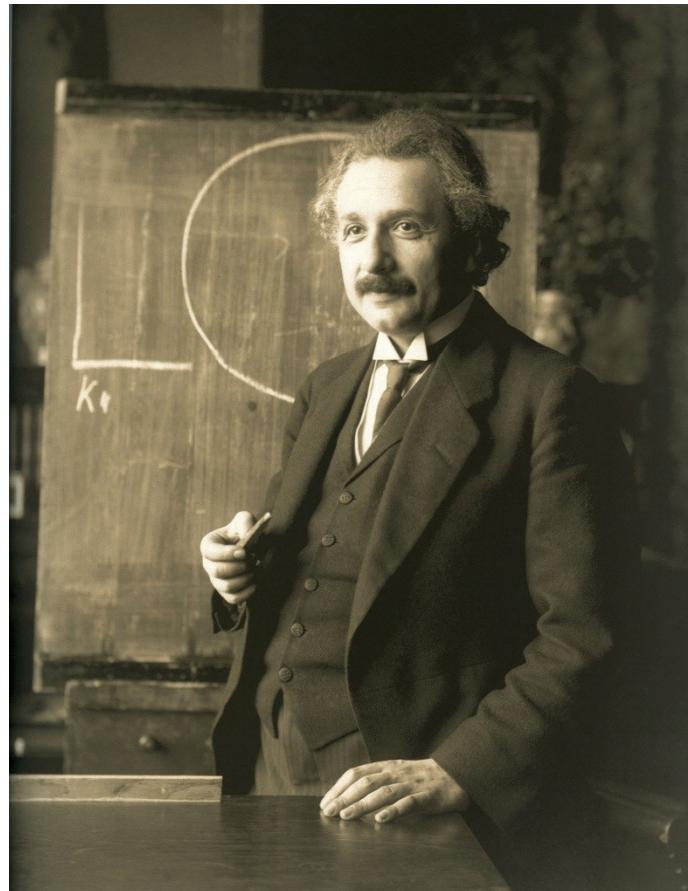
But what *is* energy?

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

$$E = mc^2$$

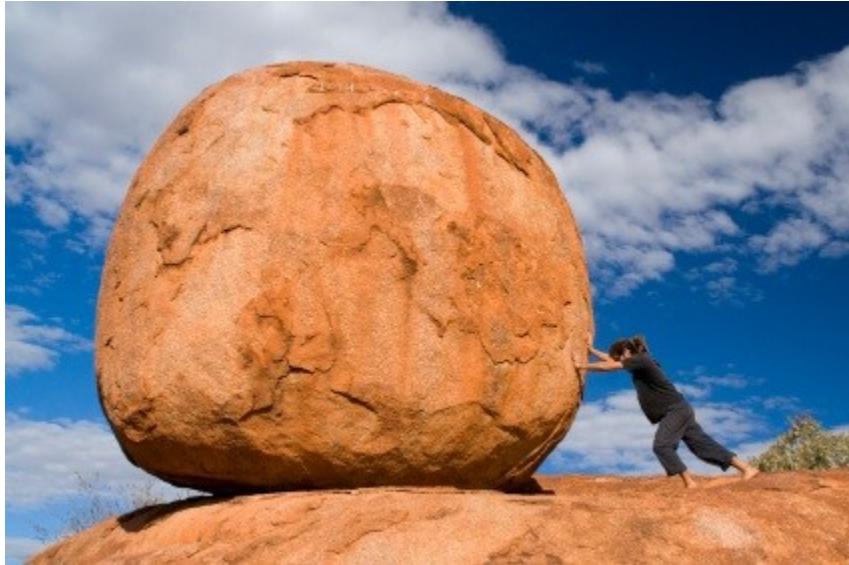
...means energy is equivalent to mass

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



What does $E = mc^2$ mean?

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



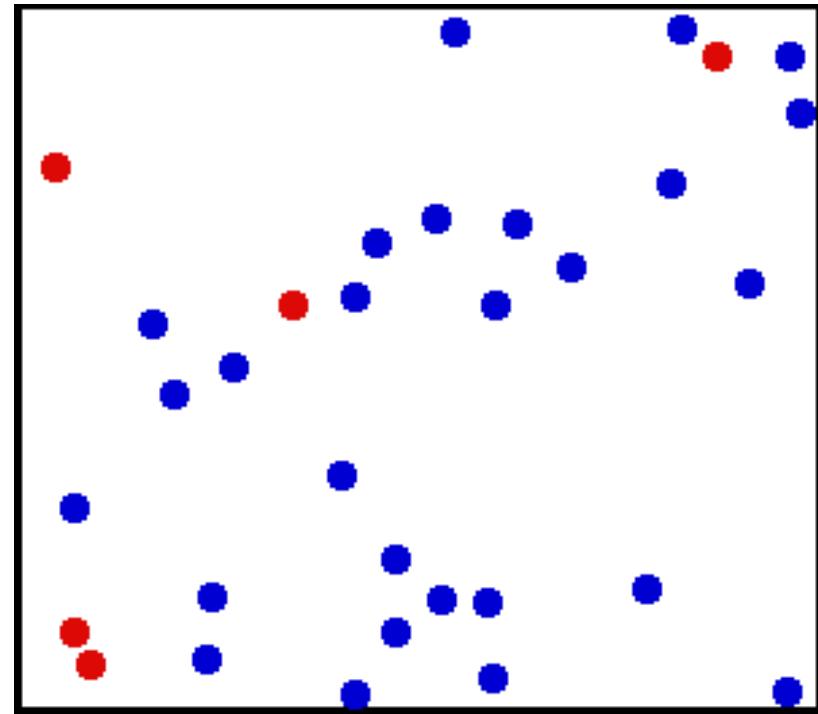
What does $E = mc^2$ mean?

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 (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



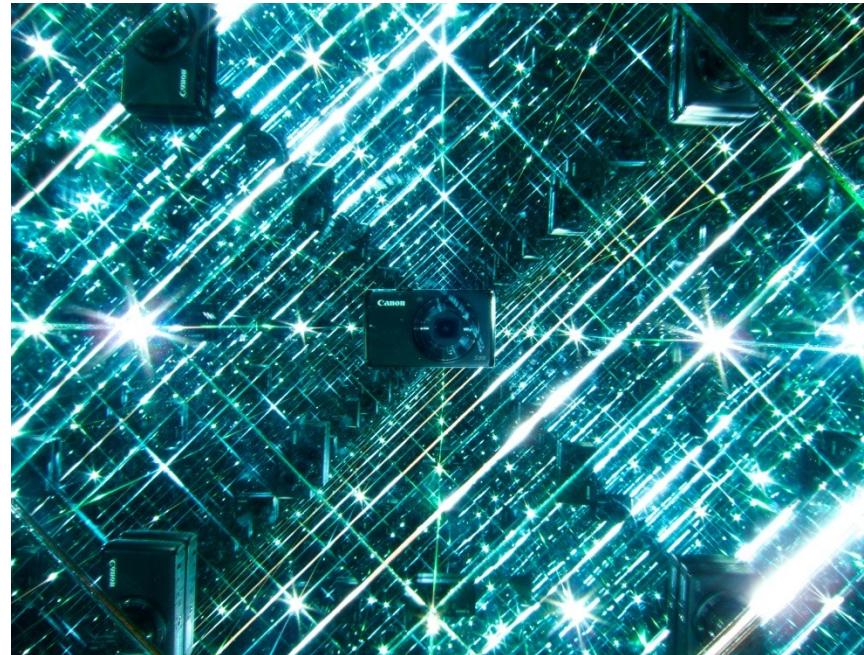
What does $E = mc^2$ mean?

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): $\Delta m = \Delta E/c^2$

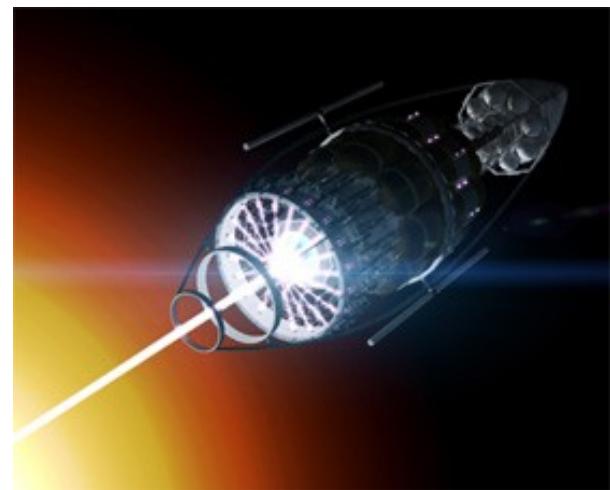
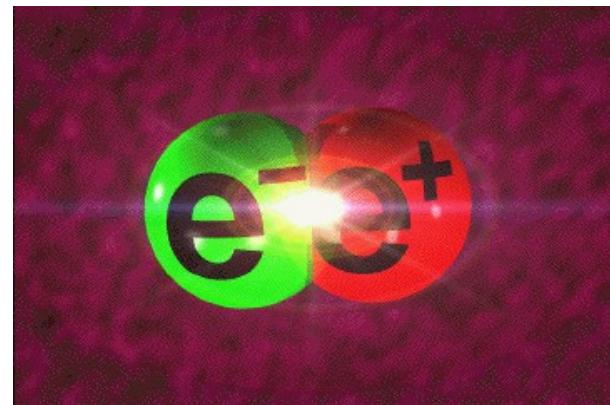
It also weighs more



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 20th 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*



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



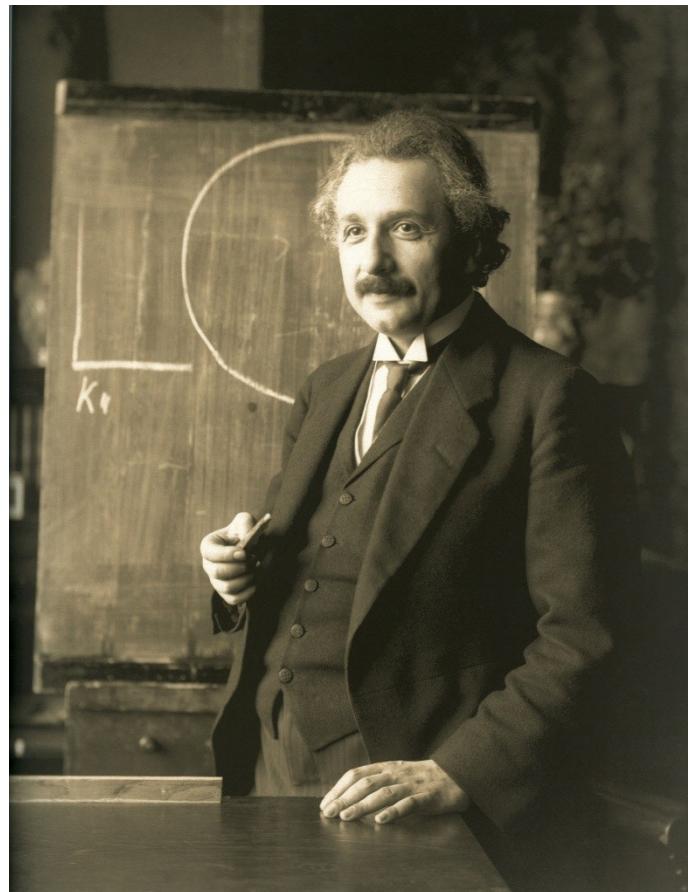
What does $E = mc^2$ mean?

We are *literally* eating the Sun

Life is *profoundly* physical

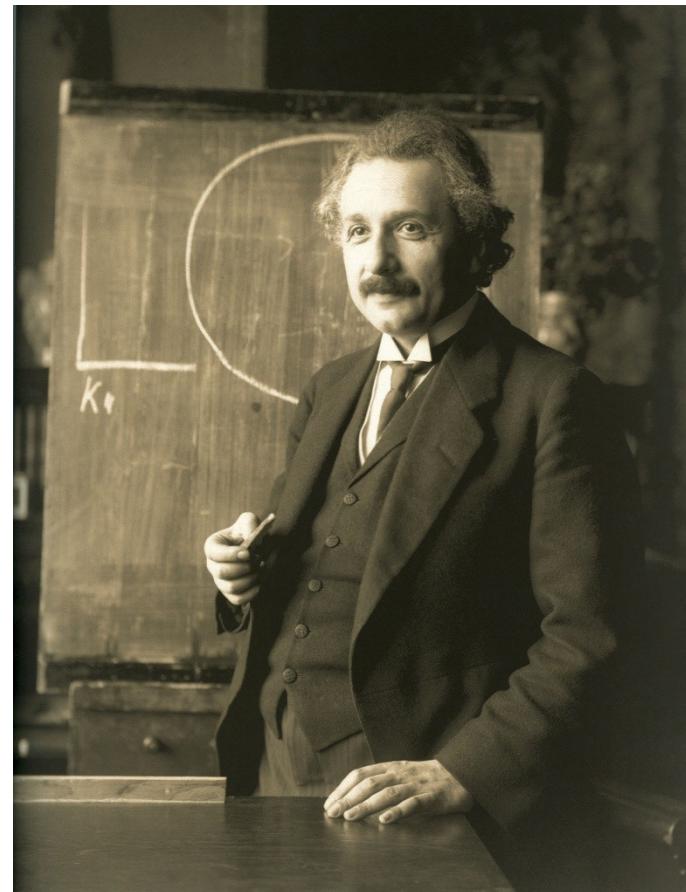
What is energy? Einstein's first deep insight:

energy = mass



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

mass-energy = warping of spacetime

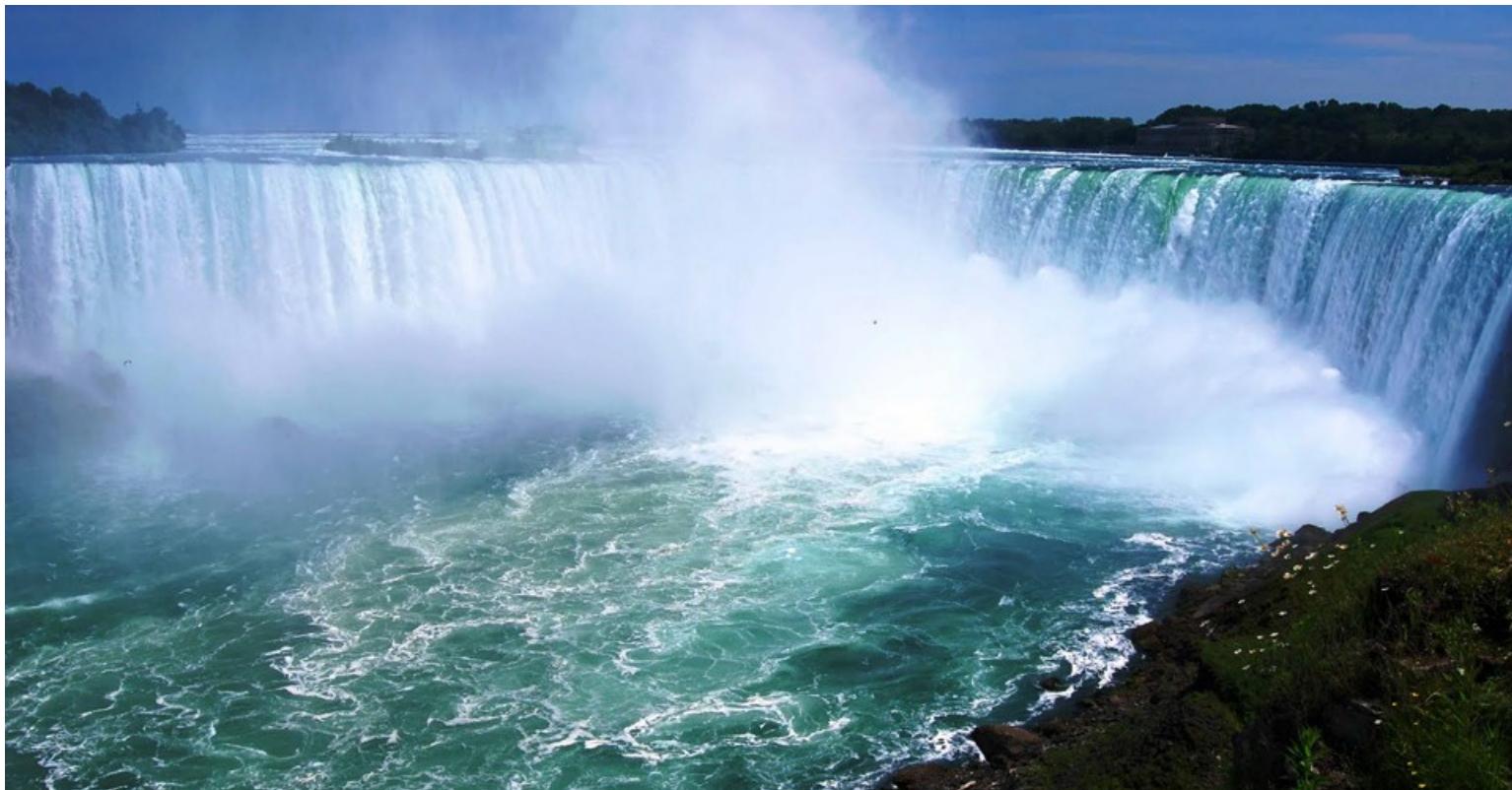




Mass-energy is the essence of all things, including life

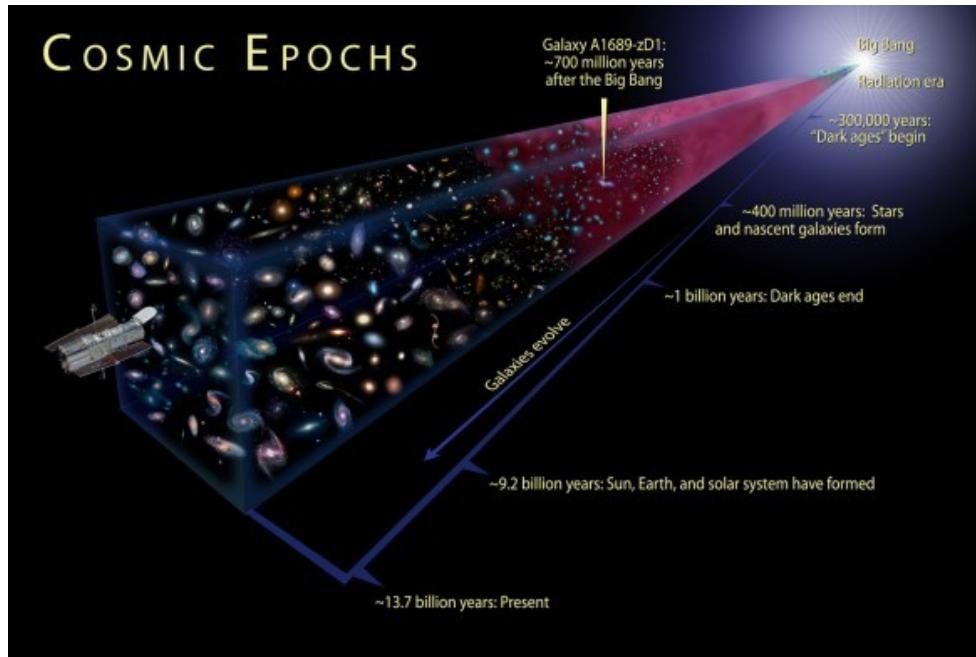
**...and it is inextricably woven into the very fabric of
space and time itself**

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



...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.



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

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



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



Useful

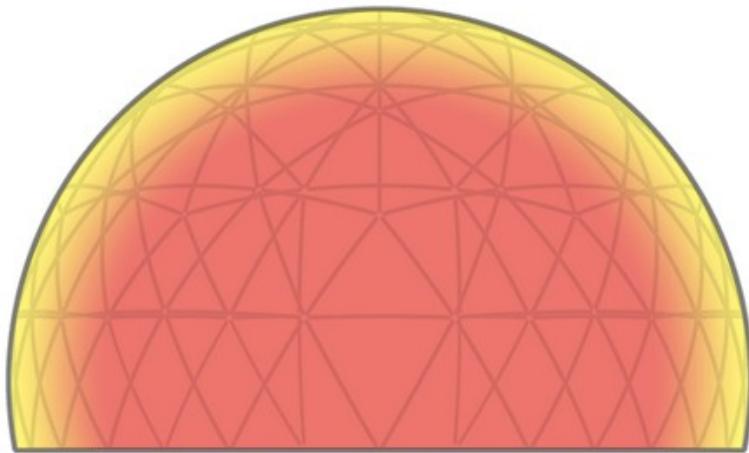


Useless

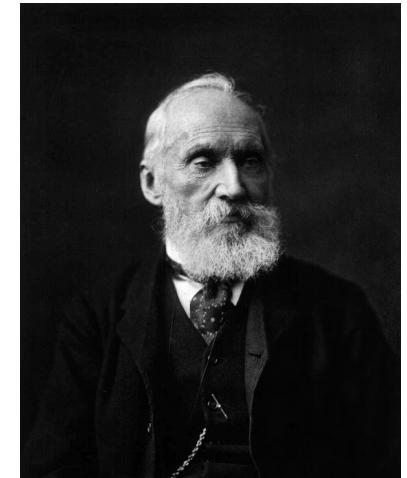
- Energy will never run out, but it “**runs down**.”
 - If the universe were to reach **equilibrium** (no **gradients** of temperature, pressure, density,...), energy could no longer **flow/transform**. “**Lifeblood**” would “**freeze**.”



- 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



- **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...

