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

Kinetic Energy

- Beginning with Gottfried Wilhelm **Leibniz** in the 1670s–80s, people eventually realized that in certain mechanical systems (of several masses m_i moving with speeds v_i), the quantity

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

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

- 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

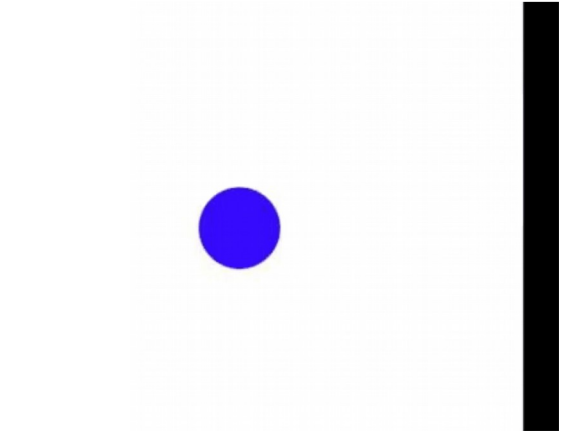
"Elastischer stoß3" by Raul Roque

Potential Energy

- When a ball collides “elastically” with a wall, it momentarily comes to rest, and so has no kinetic energy

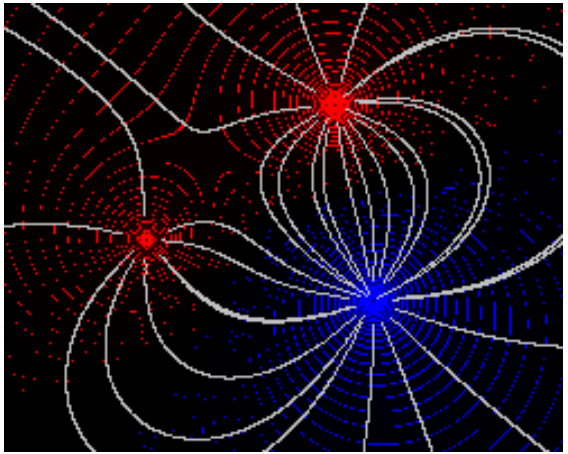
- However, it’s **shape is distorted**. Like a compressed spring, it “springs back” to its original shape and restores the ball’s original kinetic energy

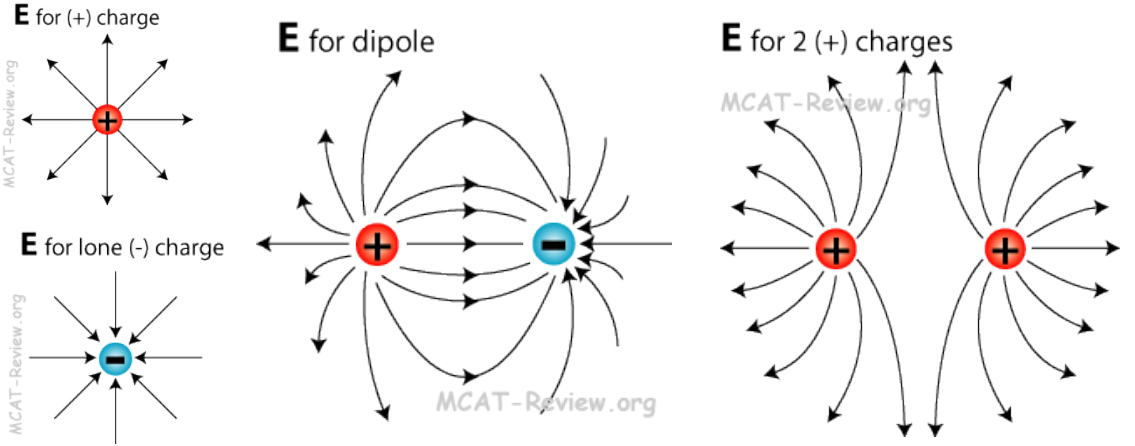
- We sometimes say that the distorted ball stores “elastic potential energy”, but it’s really energy stored in an atomic-scale **electric field** inside the ball



Potential Energy

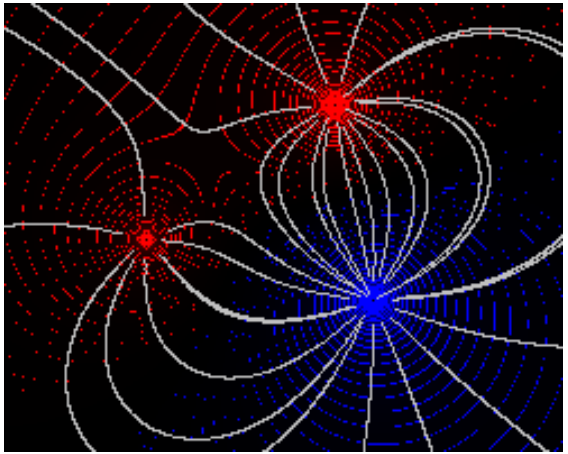
- Atoms are made of electrically charged particles: a positively-charged nucleus and negatively-charged electrons
- Each charged particle is surrounded by an *electric field*, **E**
- The electric fields of two or more charged particles *add* to produce a *net* electric field in the space around the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

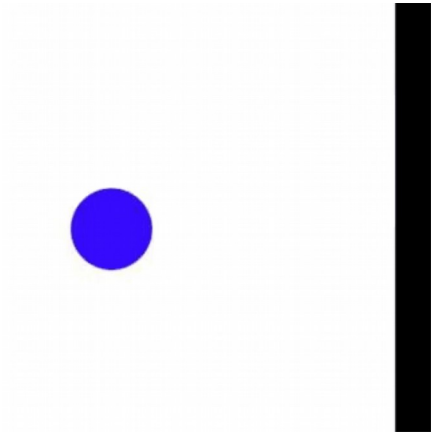




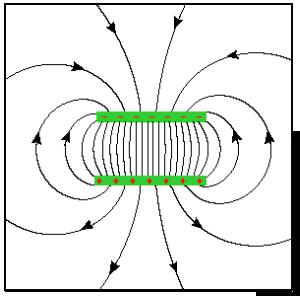
Potential Energy

- An electric field stores energy in the space between charged particles, with energy density $\frac{1}{2}|\mathbf{E}|^2$ (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)



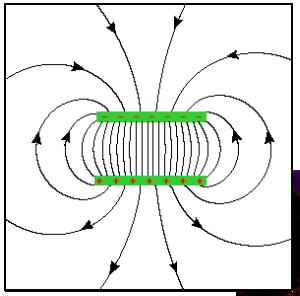


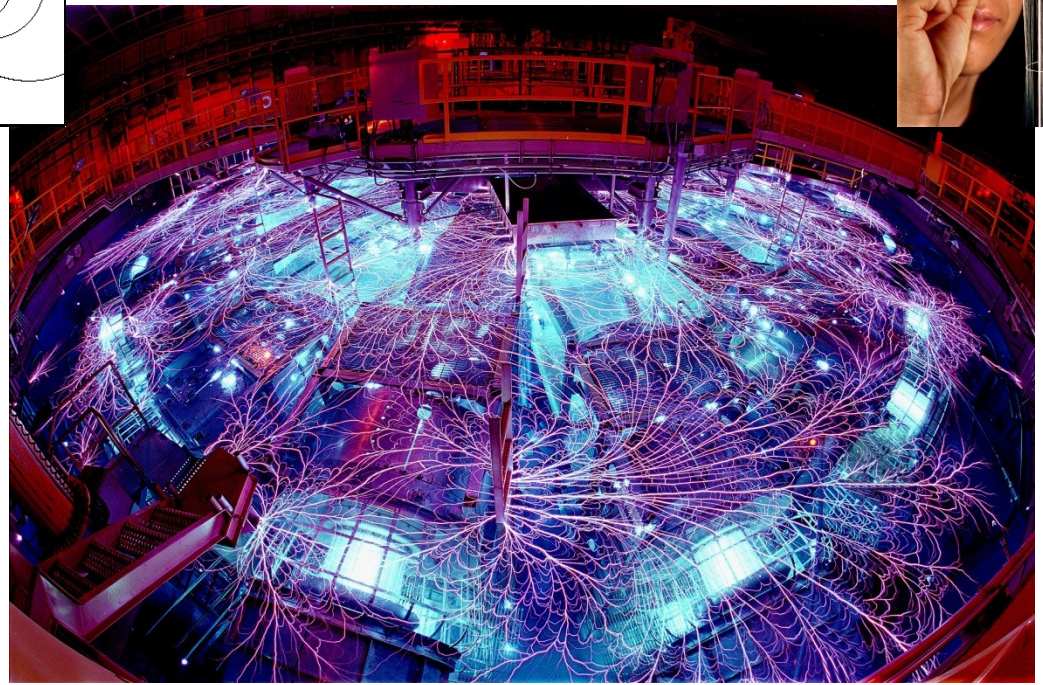
The **electric field energy** stored between two metal plates…

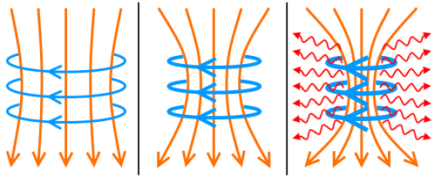


…can be converted into **kinetic energy** (in this case a 3.2 kg projectile moving at Mach 7)

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





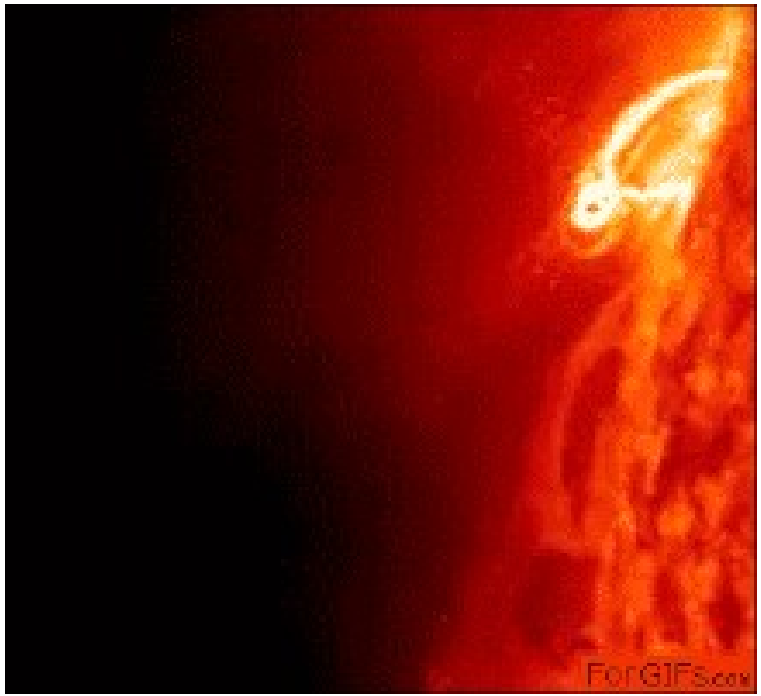


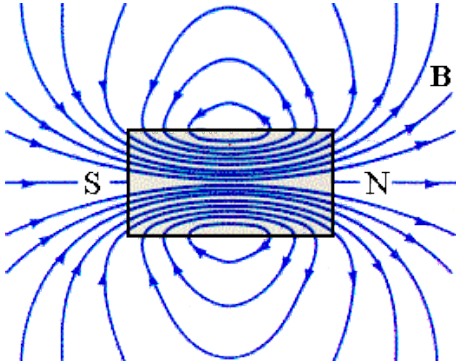
…may spark the release of more energy (via nuclear fusion) through the “Z-pinch” effect (Z-Machine at Sandia National Labs)

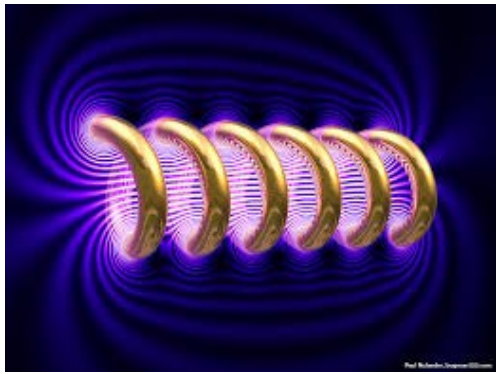
Potential Energy

- Energy can also be stored in a **magnetic field**, with energy density (joules per cubic meter)

$$\text{energy density} = \frac{1}{2}|\mathbf{B}|^2 \text{ (joules per cubic meter)}$$

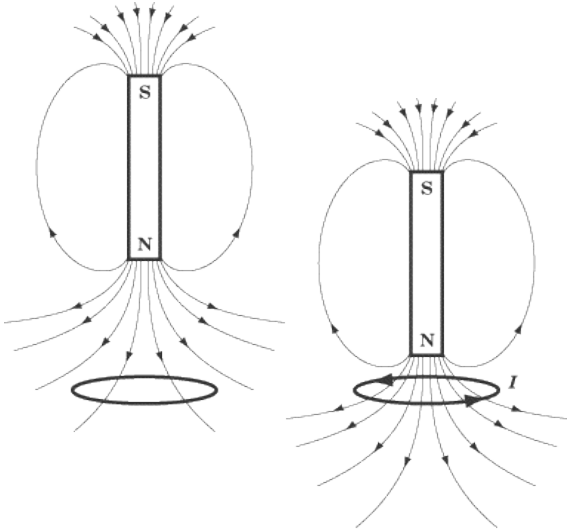


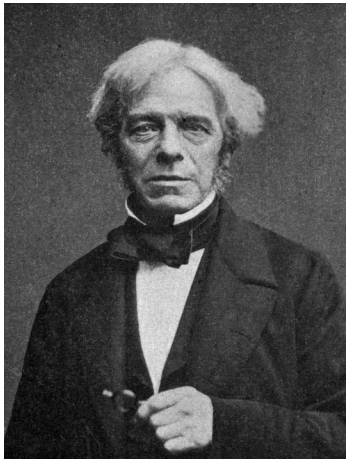




A solar flare converts magnetic field energy into kinetic energy (up to $\sim 10^{25}$ J, or *billions* of the most powerful nuclear bombs humans have built)

- 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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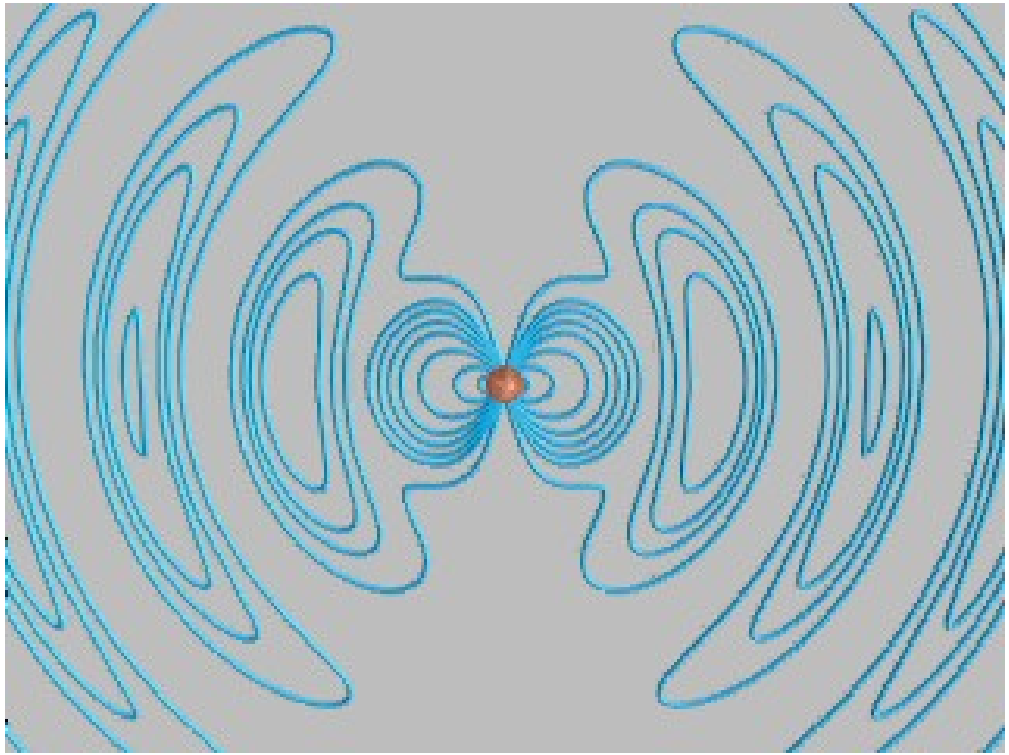

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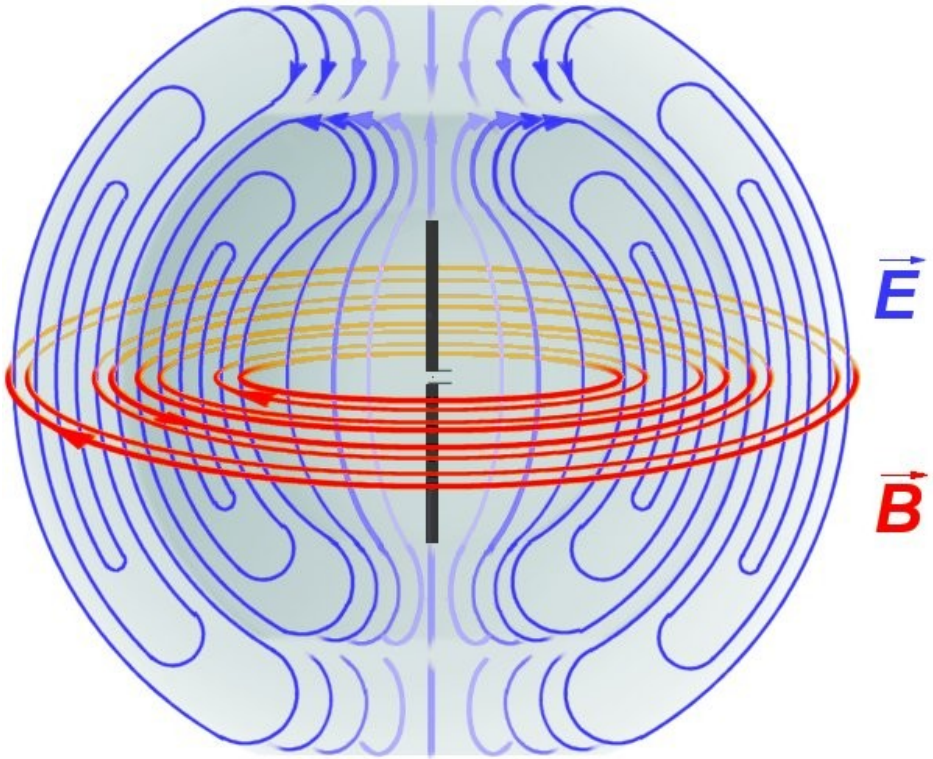
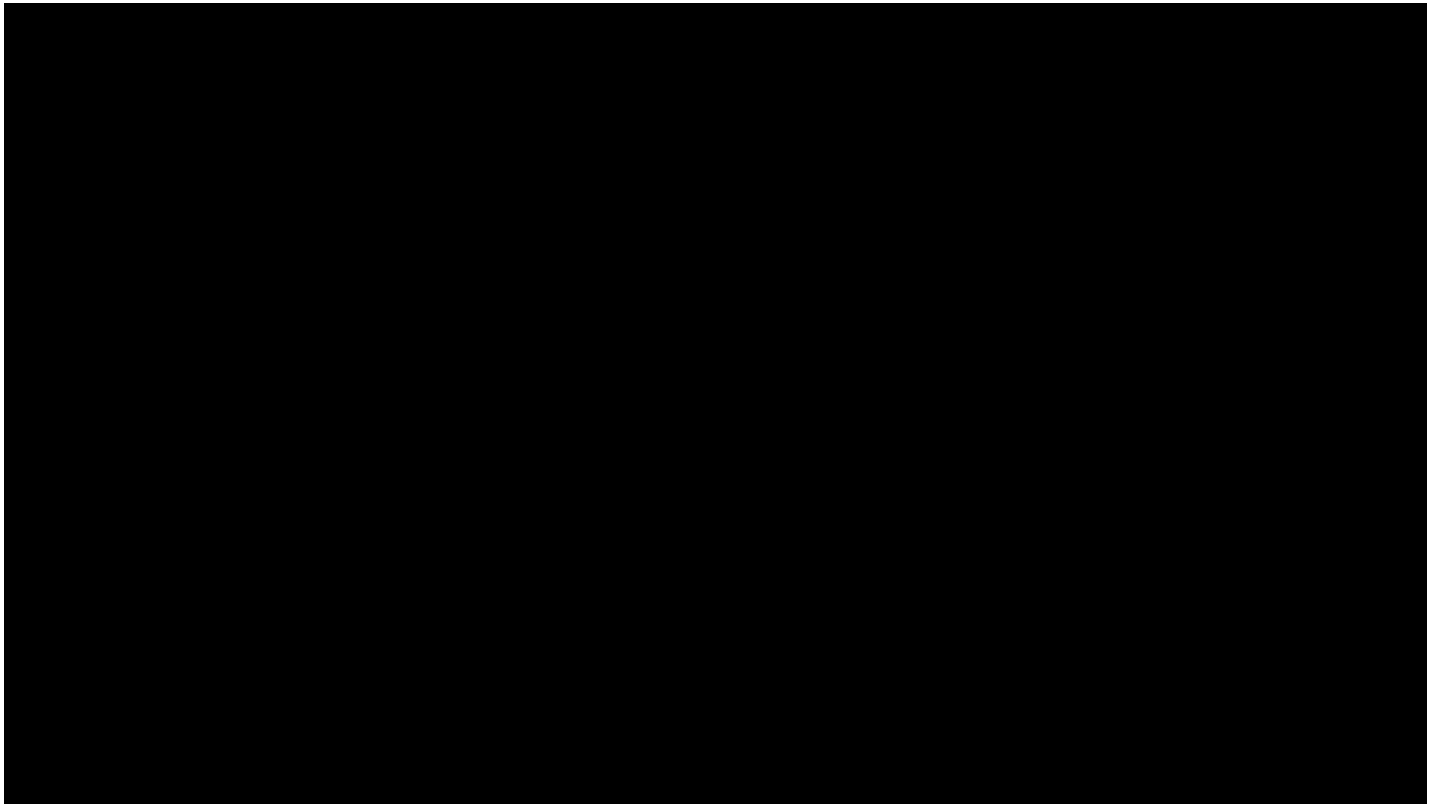


Light is potential energy stored in electric and magnetic fields, being transported through vacuum at 300 thousand km per second

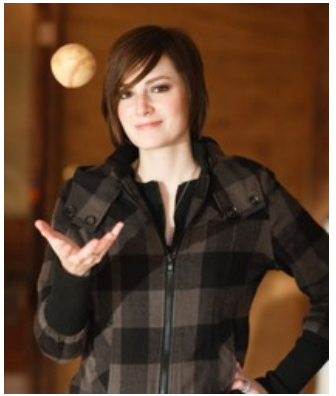
Potential Energy

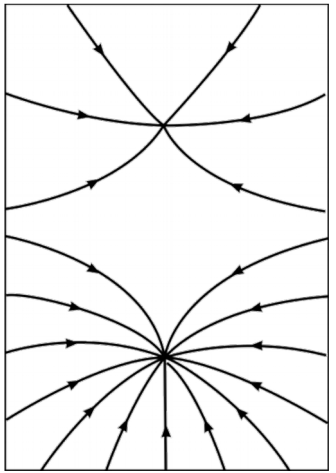
- Energy can also be stored in a **gravitational field**



Potential Energy

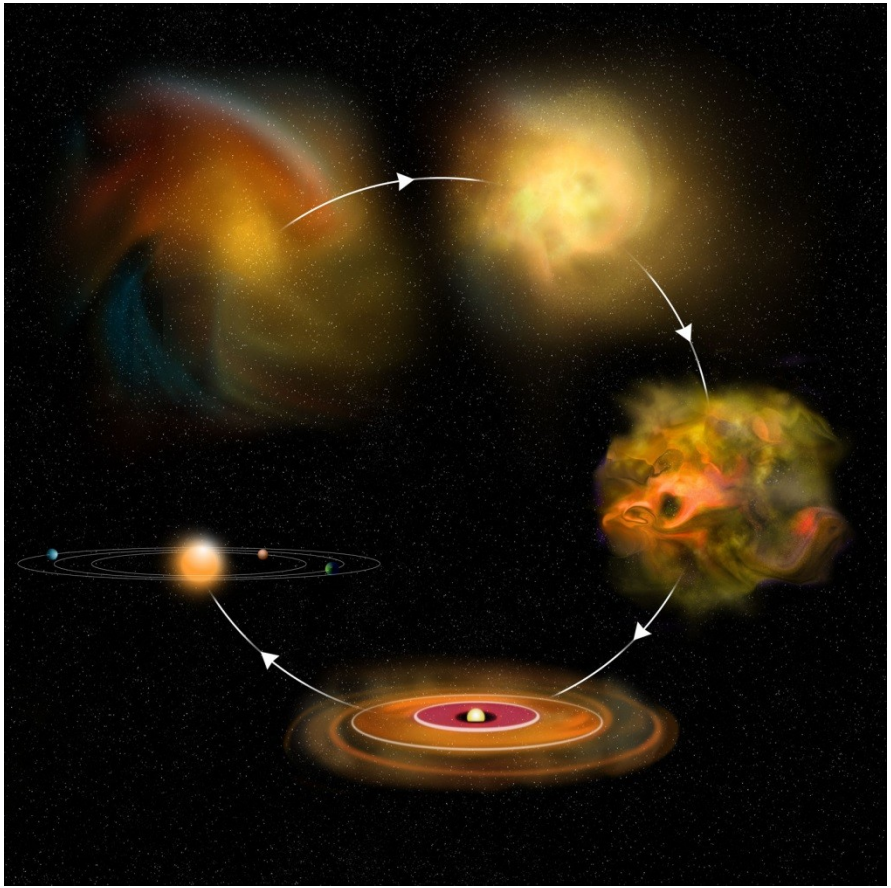
- Energy can also be stored in a **gravitational field**
- When we toss a ball up, it begins with kinetic energy. But at the top of its trajectory the ball is momentarily at rest and has no kinetic energy
- The kinetic energy has been converted into "gravitational potential energy", which is really energy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





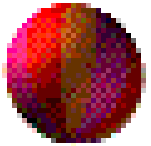
Potential Energy

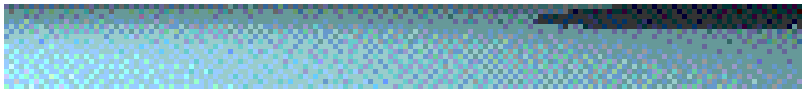
Gravitational field energy provided the spark that ignited the Sun's thermonuclear fusion reactions, which now provide virtually all the energy for life on Earth



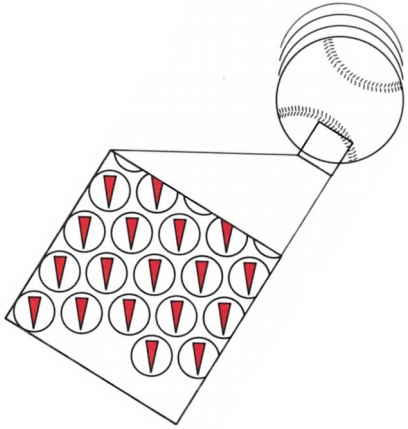
Thermal Energy

- 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…

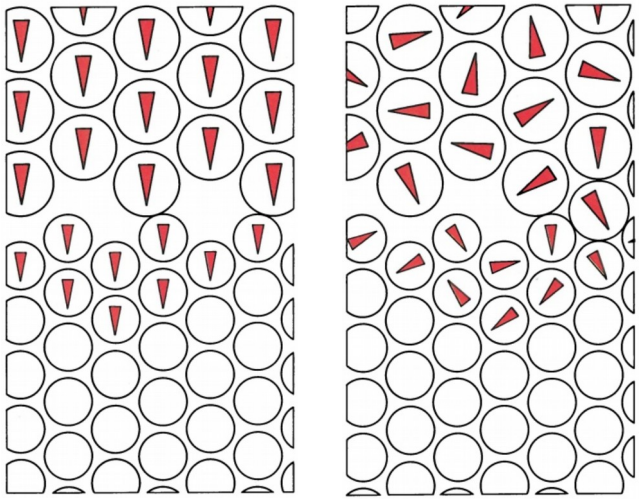




- Let's focus on what the **collisions** with the ground are doing to the **kinetic energy**:



Ball initially falling

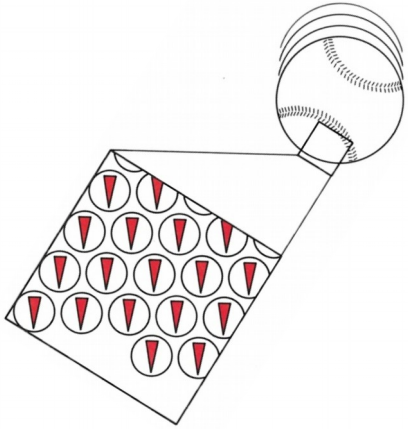


Collisions randomize the kinetic energy

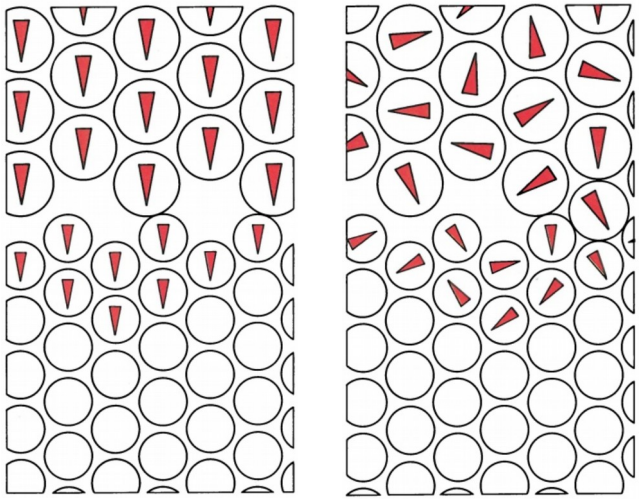
Initially:

- 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

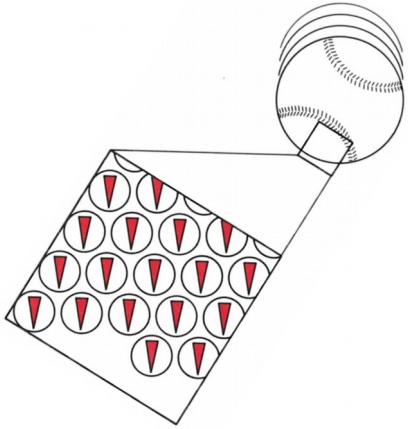


Collisions randomize the kinetic energy

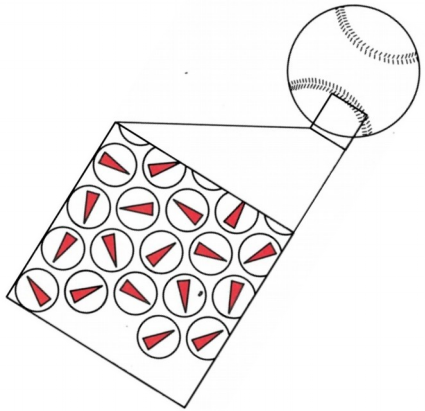
Each collision:

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

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



Ball initially falling

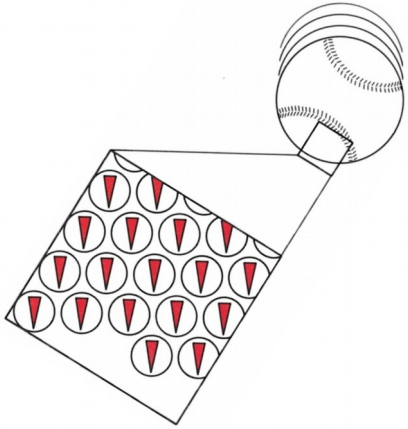


Ball finally at rest

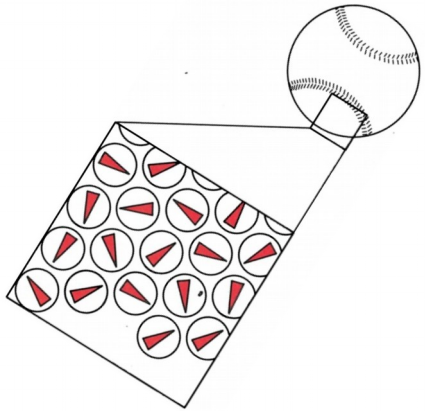
Finally:

- 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

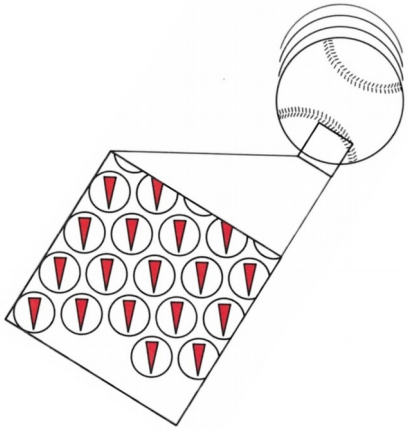


Ball finally at rest

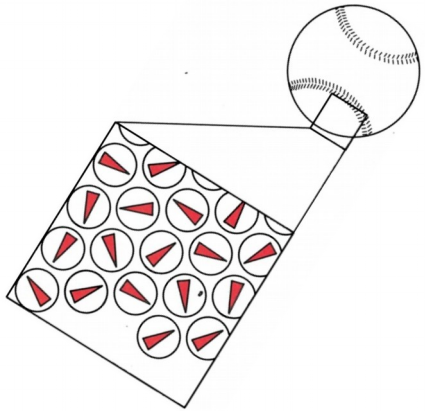
Finally:

- *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

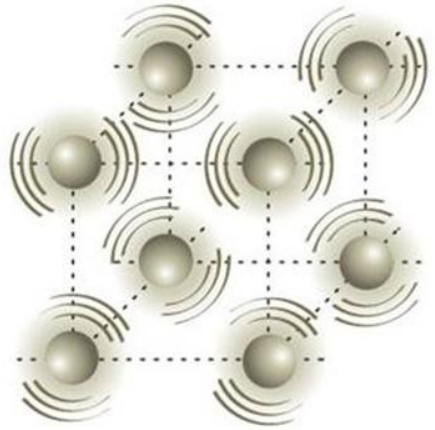


Ball finally at rest

Net result:

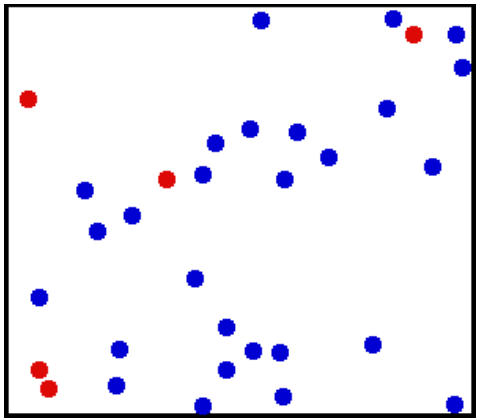
- The collisions have converted kinetic energy into thermal energy
- The **total** energy (ordered + disordered KE) is **conserved**

- 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



Vibração dos átomos

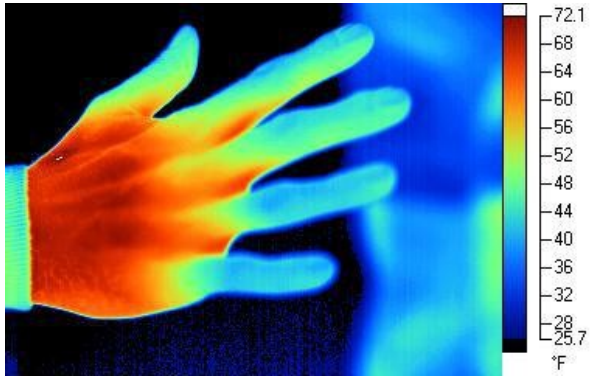
- In the case of a gas, the potential (field) energies are negligible, and the thermal energy is in the form of the disordered kinetic energy of the gas particles

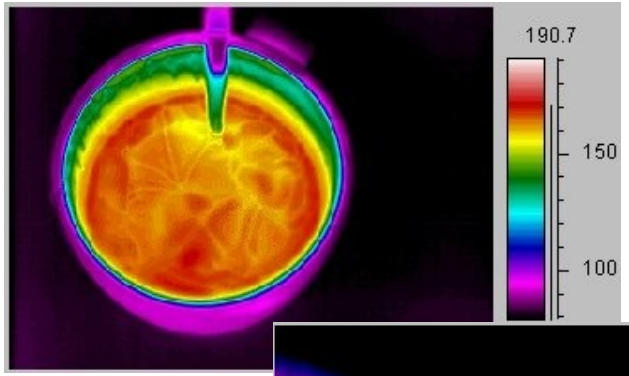


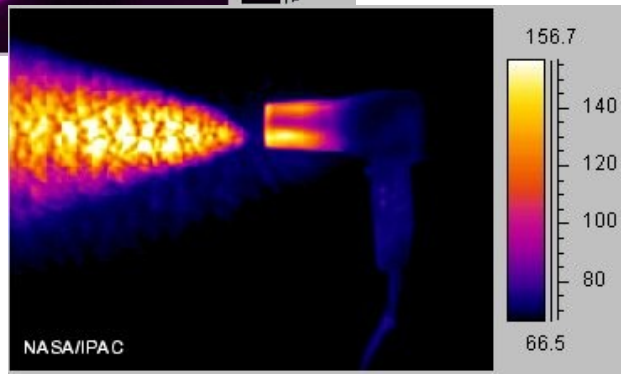
"Translational motion" by Greg L

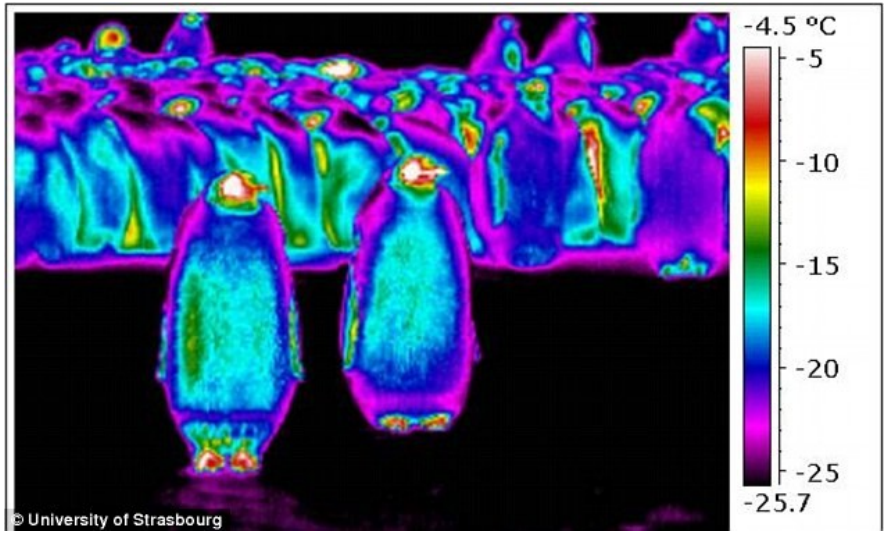
Thermal Energy

- **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.

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?

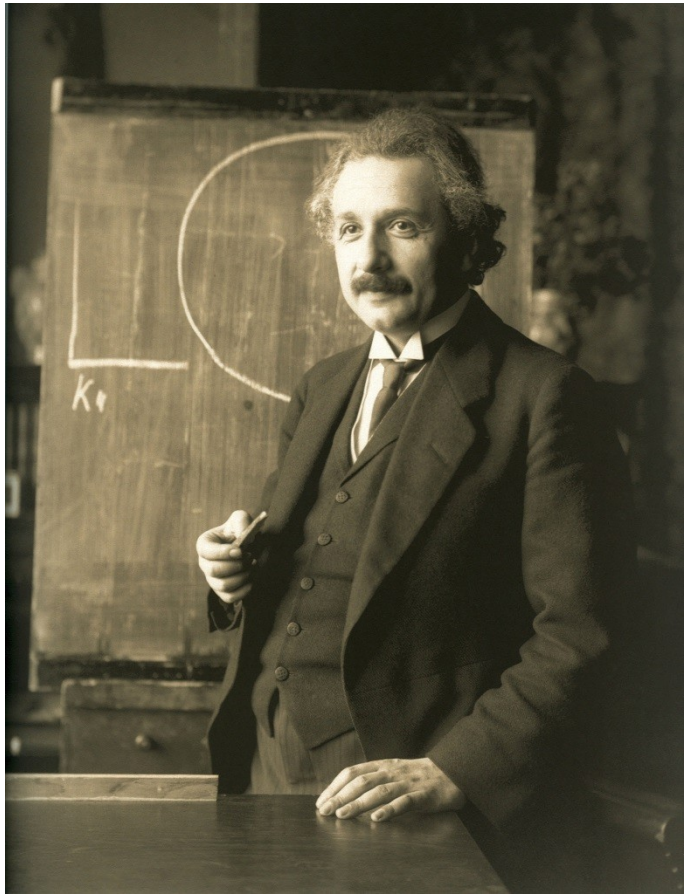
- No one knows. **Energy is a mystery as deep as the universe itself**.
- **Albert Einstein** peered most deeply into this mystery…

Einstein on Energy

$$E = mc^2$$

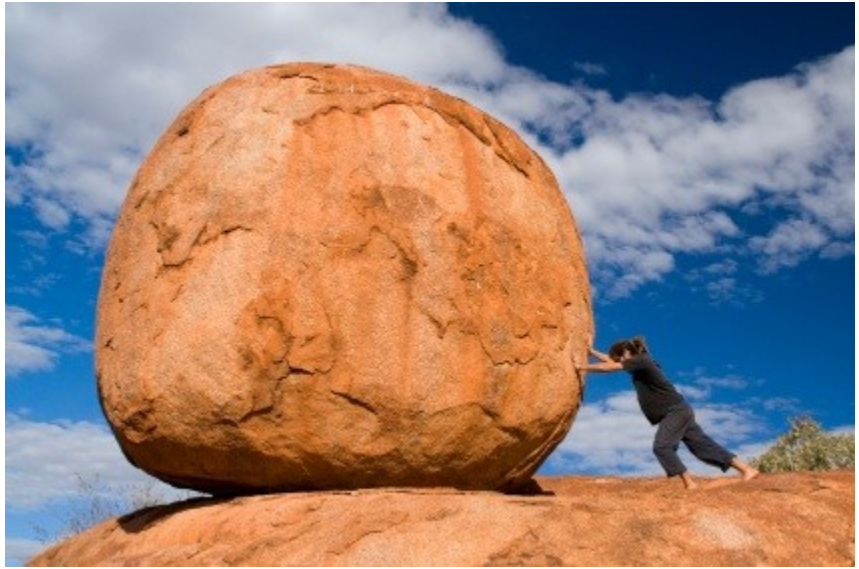
...means **energy** is *equivalent* to **mass**

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



What does $E = mc^2$ mean?

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



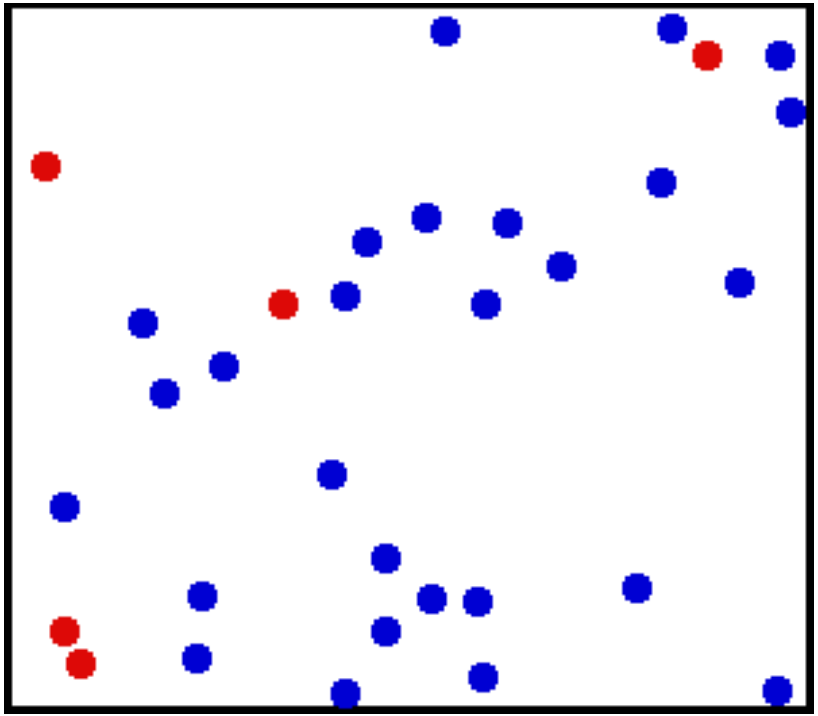
What does $E = mc^2$ mean?

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?

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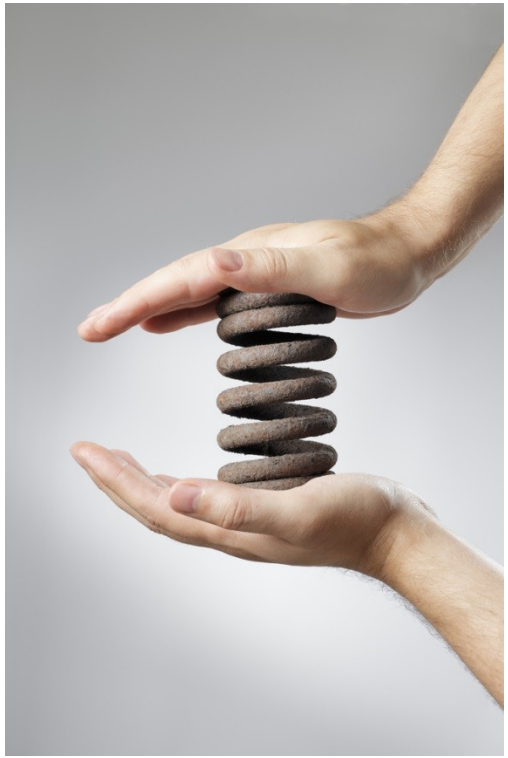
Potential energy has mass:

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

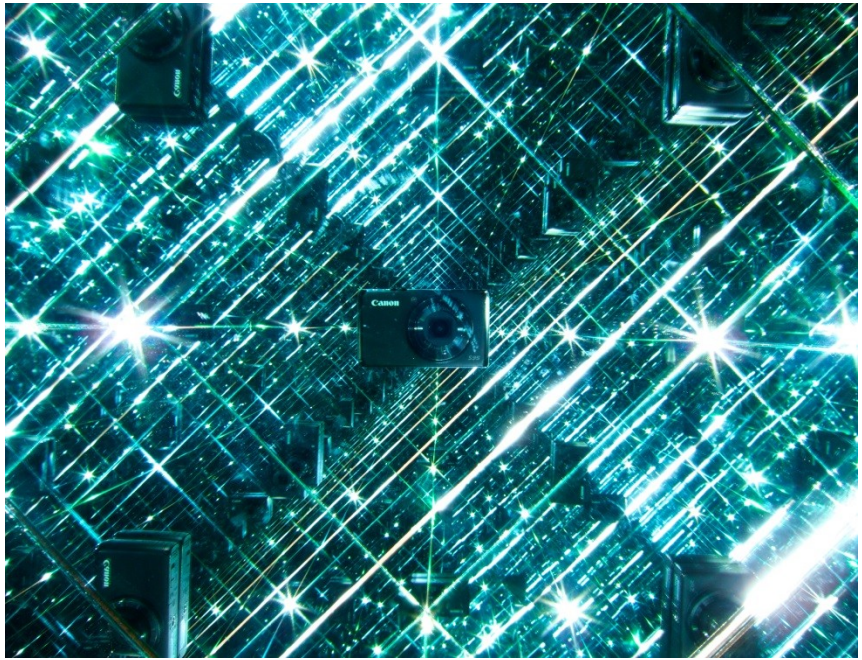
What does $E = mc^2$ mean?

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

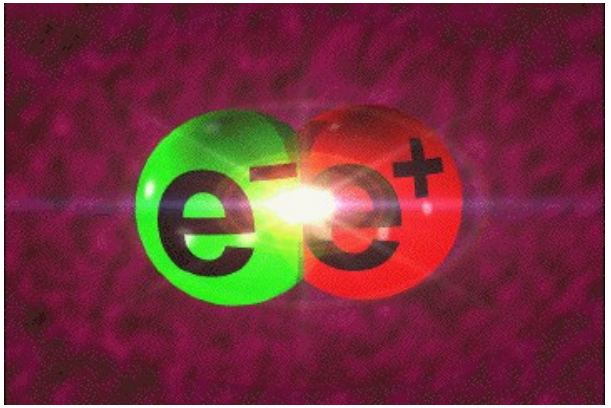
It also weighs more



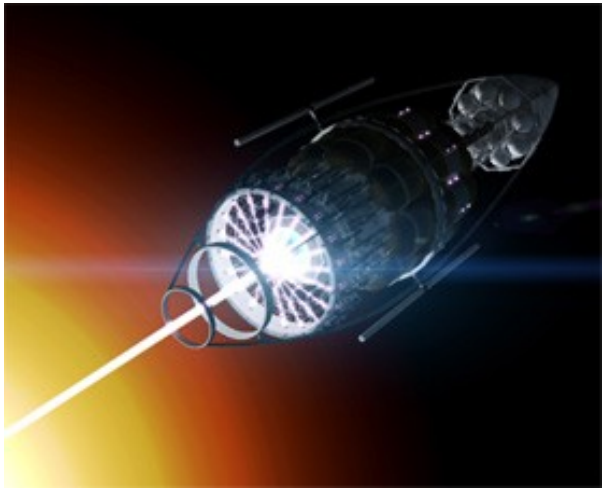
What does $E = mc^2$ mean?

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 mean?

So what?

What does $E = mc^2$ mean?

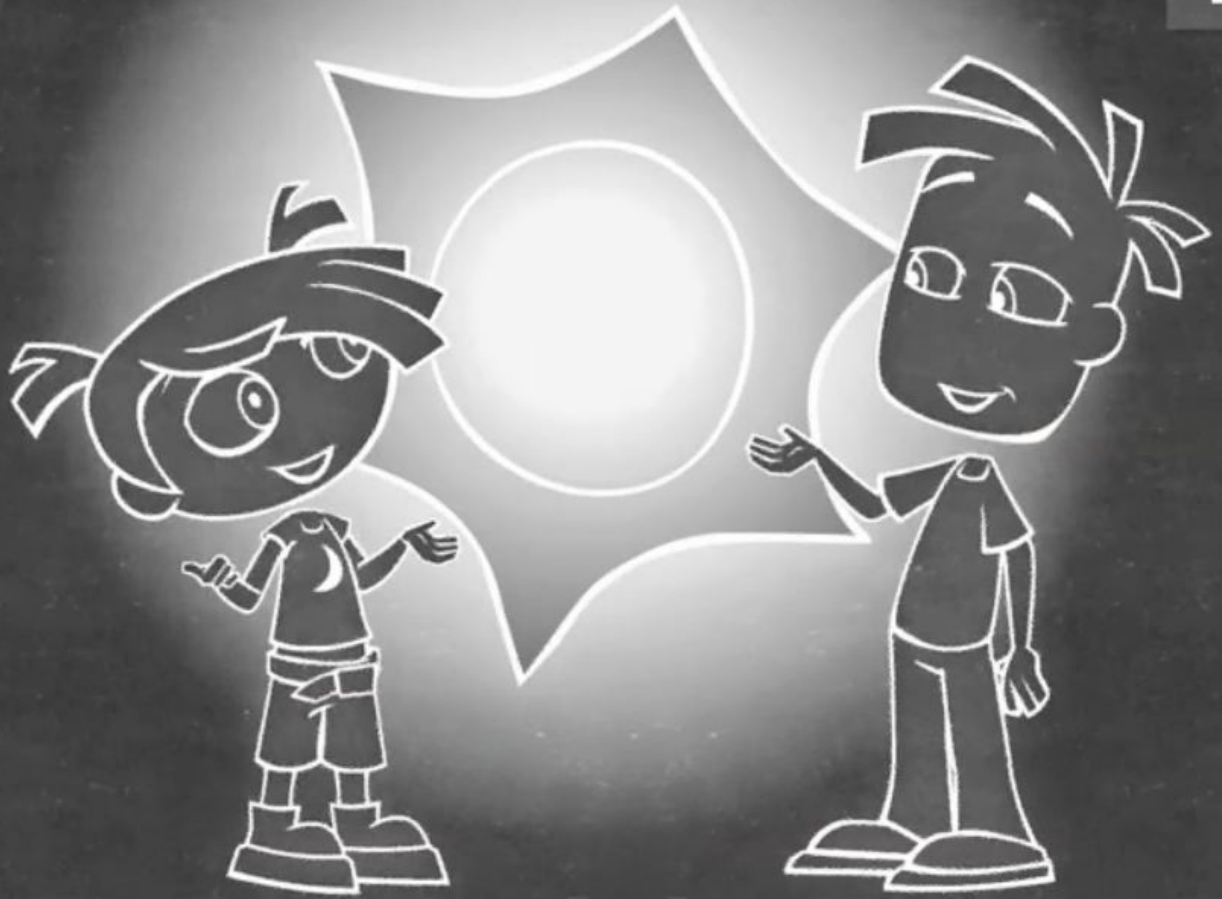
- The equivalence of energy and mass is a profound insight into the nature of reality.

- 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 yrs



Alice & Bob in Wonderland

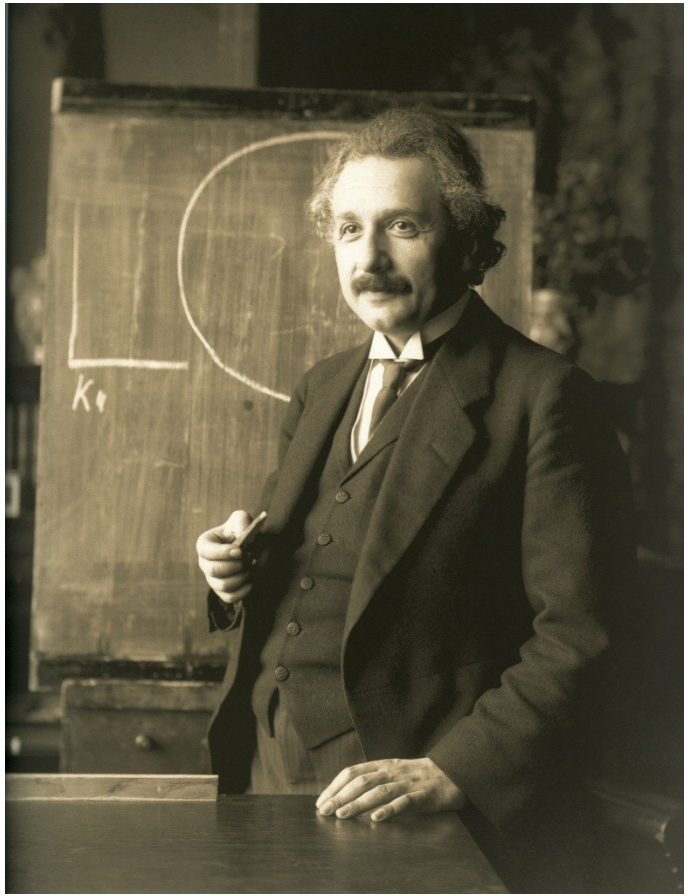
What does $E = mc^2$ mean?

We are *literally* eating the Sun

Life is *profoundly* physical

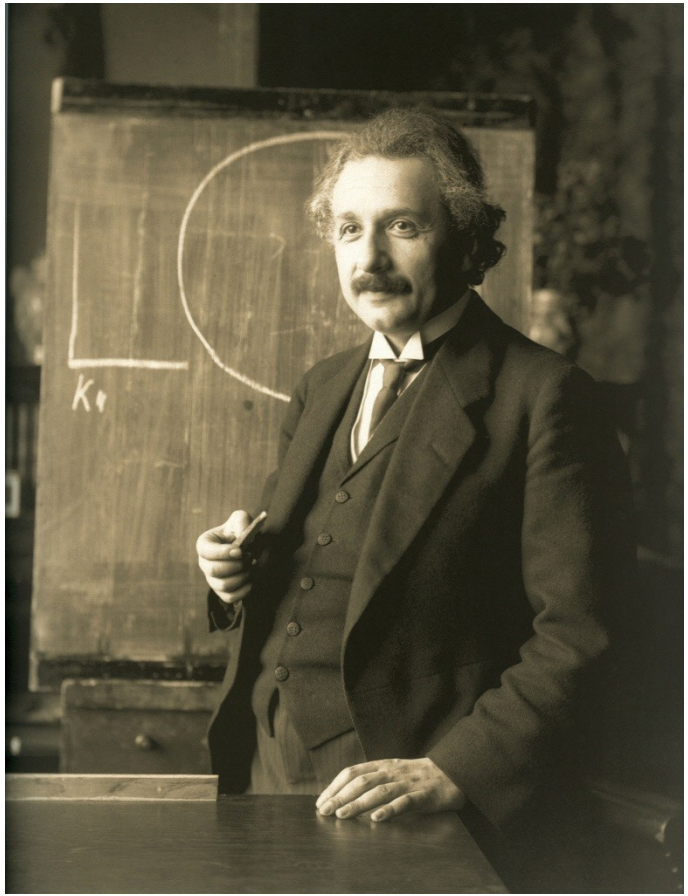
What *is* energy? Einstein's first deep insight:

energy = mass



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

mass-energy = warping of spacetime



Einstein on Energy

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

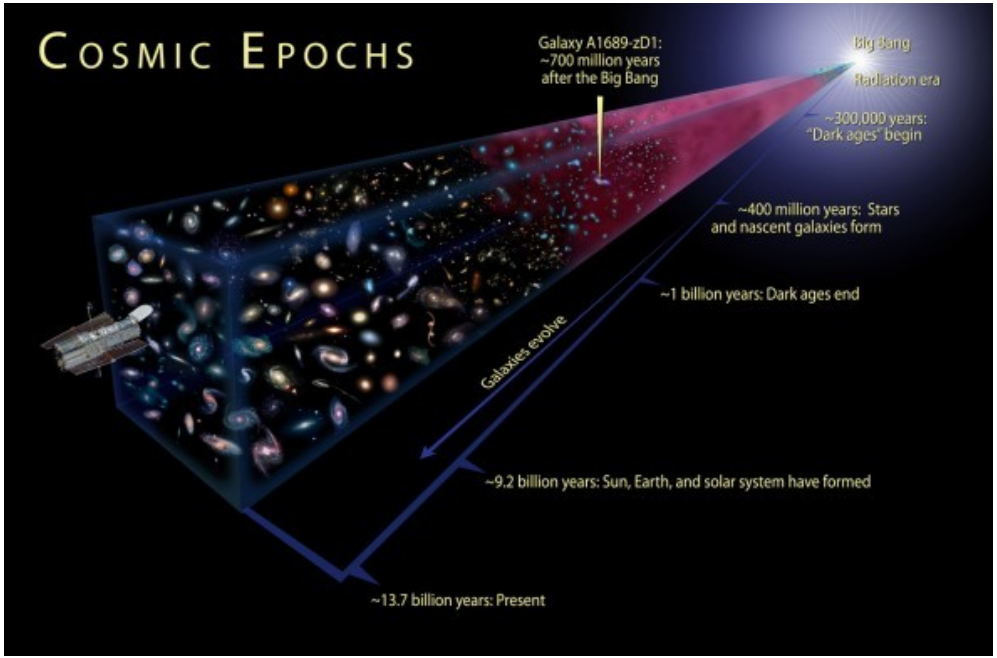
...and it is inextricably woven into the very fabric of space and time itself

…back to energy conservation

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

...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

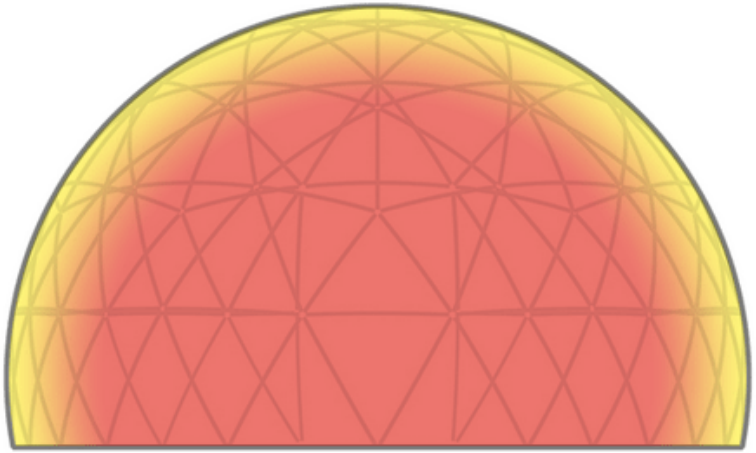
Useless

- 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.”**

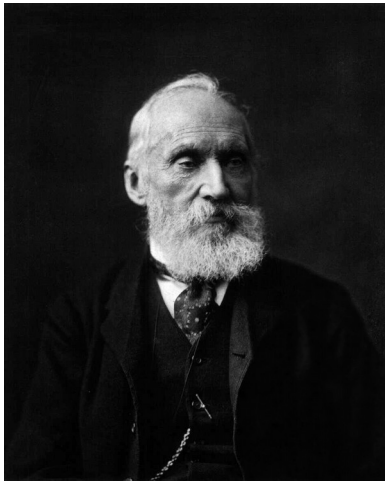
Heat Death of the Universe...and Life

- 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



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…