The fundamental concept in social science is Power, in the same sense in which Energy is the fundamental concept in physics.

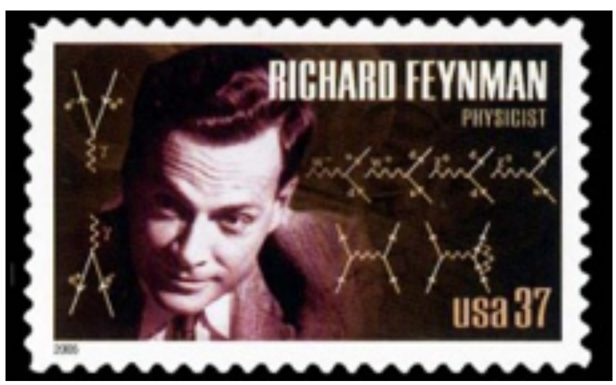
Bertrand Russell

Emmy's Insight

So we're here. Hi! In this module we'll cover conservation laws and why they exist at all. What keeps a planet rotating and orbiting the Sun?

Credit:USPS

The word "conservation" is generally understood to mean to prevent the wasteful use of a resource, to save, to protect. If we were speaking casually, we could use one of these meanings and each would know what the other meant. But "conservation" has a different meaning when used in a technical sense - it means the total value of a quantity is a constant. Richard said it nicely:



Credit:USPS

"There is a fact, governing all natural phenomena that are known to date. There are no exceptions to this law - it is exact so far as we know. The law is called the conservation of energy. It states that there is a certain quantity, which we call energy, that does not change within the manifold changes which nature undergoes. That is a most abstract idea! It says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same." - Richard Feynman

Credit: Wikipedia, Creative Commons

This conservation law is codified in something you've probably heard since grade school: "Energy is conserved; it cannot be created or destroyed." Objects have whatever energy they have from exchanges with other objects. The image above shows an example of energy being conserved. Climbing up the steps gains gravitational potential energy. Jumping off the platform converts that potential energy into energy of motion - called kinetic energy. For reference a kinetic energy is 1/2 times mass times the speed squared, 1/2 × mass × speed^2.

$$\textit{Kinetic}\ \text{E}\textit{nergy} = \frac{1}{2} \times\ \textit{mass} \times \textit{velocity}^2$$

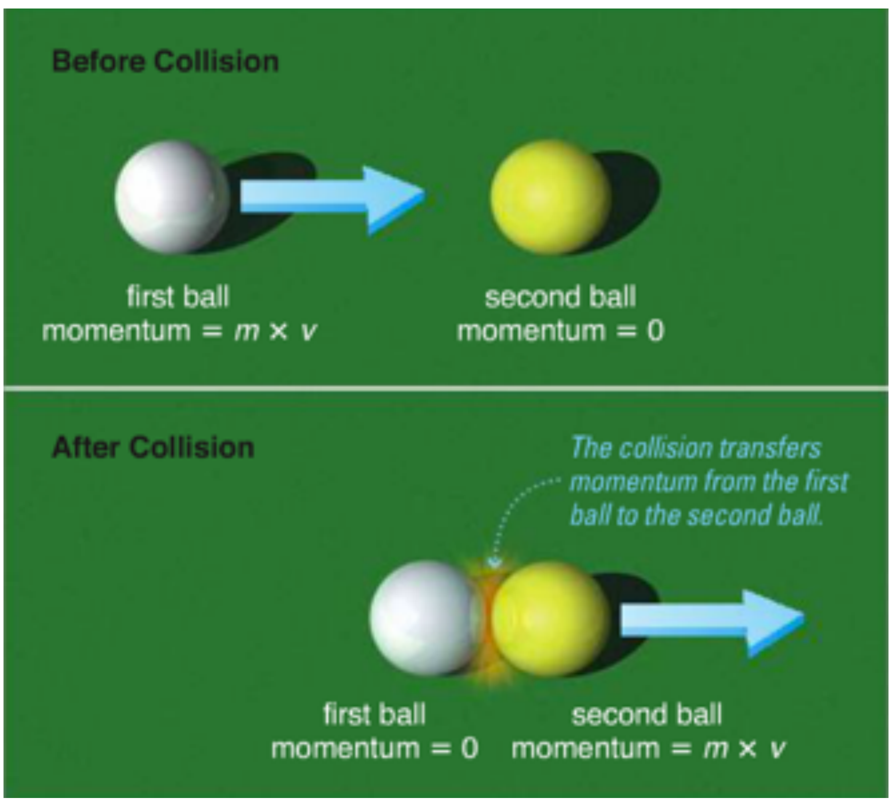

Credit: Wikipedia, public domain

All good, OK, but why is energy conserved? Why is any quantity conserved? The answer to these questions is given by a stunningly deep insight from Emmy Noether: symmetry implies conservation. Emmy is shown in the two images above.

For example, if the laws governing a system do not explicitly depend on time (that's the symmetry) then energy is conserved. This does not say things don't move around and change with time. Because they certainly do! What it says is if the rules describing these changes are the same yesterday as they are today and will be tomorrow, then energy conservation is a required outcome.

Similarly, if the rules do not depend on position, in other words if the laws are true here, there and everywhere, then momentum (mass times velocity) is conserved. One more. If the rules do not depends on orientation, upside down or sideways or right side up, then angular momentum (position times mass times velocity) is conserved.

These are the big three — conservation of energy, momentum and angular momentum that we'll be contemplating — but like any deep insight such as Emmy's, they go much further.



Conservation of momentum (mass × velocity) means an object's momentum cannot change unless it transfers momentum to or from another object. When no force is present, no momentum can be transferred so an object must maintain its speed and direction.

$$Momentum = mass \times velocity$$

An example is billiard balls as shown by the image above. One ball which is moving at some velocity, and of course the ball has mass, so the ball has a certain momentum -- mass times velocity. The second ball is just sitting there. It has mass, but its velocity is zero.

The two balls undergo an interaction such that — you know this from playing pool, if you're a good enough shot — the first ball will stop dead and the stopped ball will now move. All of the momentum gets transferred into the second ball, which hopefully goes into a pocket in the game of pool or billiards. So conservation of momentum. Mass times velocity is a constant.

Things in nature generally spin and orbit as well. We refer to this spinning as angular momentum. An angular momentum is distance times mass times velocity. It's conserved. Whatever angular momentum you start with is what you end up with at the end of the process.

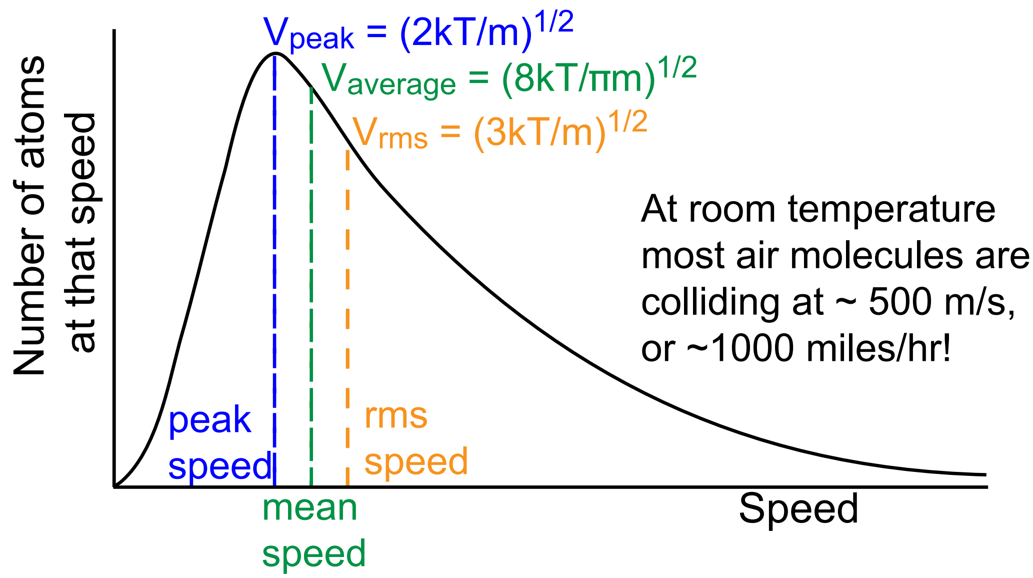
You see this all the time at, say, Olympic skating. A skater begins to spin, with their arms outstretched. They start spinning relatively slowly. The distance there is the length from the center of the body out to the hands. So they've got some angular momentum. As the skater draws their hands inwards the distance is getting smaller. But if distance times mass times velocity is always the same - something has to increase . What goes up is the velocity.
So the skater starts spinning faster and faster as the distance to the hands gets smaller and smaller. And of course, the opposite when the skater wants to slow down, they move their hands outward. That increases the distance and so the speed goes down to keep the product of distance times mass times the same. Conservation of angular momentum in action.

The image above shows the same thing happens with a planet. Conservation of angular momentum (mass × speed × distance from center of mass) means a planet's orbit cannot change unless it transfers angular momentum to another object. Our planets do not exchange significant angular momentum, so their orbits remain steady.

$$Angular\ Momentum = \ mass \times velocity \times dist.\ from\ c.o.m.$$

Where the planet gets closer to the Sun, where it gets to perihelion, the distance gets small, so the speed must go up. Oppositely, at the other side, at aphelion, the distance is large. So in order to keep the angular momentum conserved, the speed goes down. Its conservation of angular momentum that really explains Kepler's Second Law of equal area in equal time.

Credit: F.X. Timmes



A small sideline just to change topics. What is a temperature? What is it that is being measured when we say it's 100 degrees Fahrenheit outside?

Temperature is a measure of the kinetic energy of the molecules within a substance. When you record the temperature, you are measuring how fast the molecules are moving. If you have a low temperature, then each of the particles, or kinetic energy of each of the particles, doesn't move around very much. And as you crank up the temperature, the atoms, molecules, whatever it is, can move even faster, so they have a larger kinetic energy. Temperature is really about measuring the kinetic energy of the individual atoms.

Fun, geeky fact! At room temperature the air molecules are zipping around with an average speed of about 500 m/s or 1000 miles/hour! That's right, every second your body is being hit by air molecules traveling faster than most bullets. We don't feel them because there are so many hitting us at all possible angles. We do feel the net result, which we call air pressure.

Thanks, bye bye!