Energy; You can’t live without it.

Energy can take many forms: kinetic energy, potential energy, heat energy, electromagnetic energy, and so on. “Work” has a technical meaning in physics: One does work when a force is applied to an object, unless the force is exactly perpendicular to the displacement of the object. In other words work is done as long as there is a “component” of the force along the object’s displacement. And if there is no displacement, the force does no work. Some examples follow:

Kinetic Energy is the energy of motion. This is \( \frac{1}{2}mv^2 \) for a particle of mass \( m \) and speed \( v \). This formula is Newtonian, and applicable for speeds much less than the speed of light. For relativistic mechanics (speeds approaching the speed of light) Einstein introduced a more general formula, which simplifies to the Newtonian form when \( v \ll c \).

Potential Energy is the energy associated with the location of a particle. A book held above a desk has higher (gravitational) potential energy than a book on the desk. Notice that it takes work to raise the book from the desk to a location above it.

Heat energy is energy transfer to a body without doing work. It is the kind of energy transferred from your hand to an ice cube to raise the temperature of an ice cube.

Electromagnetic energy is energy contained in the existence of electromagnetic fields.

Rest energy is a part of a particle’s total energy. It exists by virtue of having mass according to the equivalence \( E = mc^2 \).

Conservation of Energy: The total energy of an isolated system cannot change. (Energy can change from one form to another, but the total amount of energy remains constant.) Notice that rest energy must be included in the energy bookkeeping. This conservation law is one of the most strongly held by scientists: there is enormous experimental evidence that when all the bookkeeping is done correctly, the total energy of an isolated system is constant. However, it is emphasized that some day systematic counter evidence could appear, in which case, deepest held ideas will have to be modified. For now: conserve energy in all processes in isolated systems. For systems which are not isolated, be careful to account for energy coming in or going out in the form of work or heat or whatever.

Some examples:
Raising a book from the desk to a position above it takes work. The potential energy is raised, in this case gravitational potential energy. Releasing the book turns that potential energy into kinetic energy. The book smashes into the desk and comes to rest. The kinetic energy just before contact gets converted to sound energy (elastic energy in the air) and to thermal energy (the temperature of the desktop and book are, in principle, raised a bit). We don’t need to consider rest energy in this type of example since the same book is involved throughout and it “cancels out.”

A satellite orbiting the Earth has both kinetic energy and (gravitational) potential energy. Notice that in a circular orbit the gravitational force of the Earth on the satellite is directed perpendicularly to the displacement throughout the motion. No work is done on the satellite (once in the circular orbit). Neglecting tiny air friction effects, the potential + kinetic energy of the satellite remains constant (and these are the only forms of energy we need to consider in this example).

A neutron at rest in the laboratory decays (“beta decay”) into a proton + electron+neutrino. The initial energy of the system (neutron) is only rest energy. After decay, the energy is partly rest energy of the “offspring” particles (proton, electron and neutrino) and partly kinetic energy of these items. The total energy before the decay must equal the total energy after the decay. (Conservation of energy.)

An atom of Sodium in an excited state de-excites and emits a (yellow) photon. Doing the energy bookkeeping carefully, one says that the total energy of the Sodium atom in the initial quantum state (which includes the rest masses of the nucleus and electrons, the potential energy of electrostatic interaction of all the electrons among themselves and with the charged Sodium nucleus, and the kinetic energies of the electrons) must equal the total energy of the Sodium atom in the final state + the photon energy $hc/\lambda$ where $\lambda$ is the wavelength of the emitted photon.

Alpha decay. A nucleus of uranium-238 at rest emits an $\alpha$-particle, i.e., a helium-4 nucleus, and “transforms” into a thorium nucleus. The only energy at the start is the rest energy of the uranium atom. After, there is kinetic energy of the $\alpha$-particle and of the recoiling thorium atom. Plus there are the rest energies of the $\alpha$ and thorium products. The total energy before must equal the total energy after.

Exercises:

1. A hydrogen atom is in a state with energy $-13.6$ eV., and it makes a transition to a state with energy $-3.4$ eV. (a) The second state has lower energy (b) The second state has higher energy. (c) The second state could have higher or lower energy depending on the nucleus.

2. In the situation of ex.1, is the transition (a) initiated by the absorption of a photon (b) accompanied by the emission of a photon (c) could either involve absorption or emission of a photon.

3. In the situation of ex. 1, if a photon is involved, what will its energy be?
4. From an energy perspective, describe Galileo’s experiment of rolling a ball down a plane.

5. A rock is whirled on a string (circular orbit and constant speed). Analyze the situation from an energy point of view, i.e, Is the energy of the rock changing? Is there a force on the rock? Is work done on the rock by the string?