POTENTIAL ENERGY

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As we stated in the page on kinetic energy, energy in physics is the ability to do work, and work, in turn, is defined as the product of a force and the distance over which it acts. If a single force F acts on a constant mass m over a given distance, it will cause the mass to accelerate with a constant acceleration a, where these three quantities are related by Newton's law: $F=ma$. It is important to realize that this formula is a mathematical expression of Newton's assumption (based on observations) of how the world works. It is not the end result of some complicated mathematical derivation; it is simply stated as the starting point for Newton's version of physics.

From the page on kinetic energy, we can see that the result of a force acting on a mass for a certain time is that the mass speeds up (due to its acceleration) and after a time t, it will have a velocity $v=at$. The energy transferred to the mass by the force is all kinetic energy (energy of motion), and has the value

$$E_K=\frac{1}{2}mv^2 \tag{1}$$

In order for this to happen, the force has to be completely unopposed, which is virtually impossible to arrange in the real world. A mass falling due to gravity may seem to be unopposed, but the friction with the air works against the gravitational force, so that the velocity after a given time in free fall will be less than $v=at$. In fact, a mass falling through the Earth's atmosphere has a maximum attainable velocity known as the *terminal velocity*, whose value depends on the mass and the shape of the object. A sheet of paper weighing a few grams reaches its terminal velocity much faster than a small iron pellet of the same mass.

In the case of objects falling through air, the energy due to the gravitational force that is not converted into kinetic energy of the falling object is transferred to the air molecules through which the mass falls. The energy may show up in the form of heat or turbulence in the air, both of which are forms of kinetic energy since they are due to the motion of the air molecules.

But what happens when we actively oppose a force by moving a mass against the direction in which the force acts? We do this whenever we pick up some object, such as lifting a pencil off a desk. To do this, we are generating a force from the muscles in our arm (which is ultimately electrical force, but never mind that for now). If we raise the pencil at a constant velocity, then the amount of force we are generating is exactly equal and opposite to the gravitational force pulling the pencil down. To see this, remember Newton's first law: an object with no net force acting on it will either remain at rest or move with a constant velocity. If we are moving the pencil at a constant velocity, it must have no net force acting on it, so the upward force we are generating must exactly balance the downward force due to gravity.

However, the force we are exerting to lift the pencil acts through a certain distance, so by the definition of work, we should be transferring some energy to the pencil. Since there is no acceleration, there is no change in the velocity, so clearly this energy is not showing up as kinetic energy. Where is it going?

This is where the idea of *potential energy* comes in. Whenever work is done by one force against another force, the mass is 'storing' this work as potential energy. If the first force (our arm lifting the pencil) is removed (we let the pencil go), then the second force (gravity) is free to act on the object and convert this stored energy back into kinetic energy (the pencil falls, and accelerates as it does so).

As Galileo famously showed, and as countless high school physics students have verified ever since, the gravitational force on an object near the surface of the Earth is proportional to the object's mass, and can be written as

$$F_g = mg \tag{2}$$

where g is the acceleration due to gravity, with a value of approximately 9.8 metres per second per second. What this curious set of units means is that for every second in free fall (ideally in a vacuum), an object's velocity increases by 9.8 metres per second.

Given the gravitational force, we can find how much work we have to do to lift an object by a height h: we need to resist a constant force through a distance h, so we are doing an amount of work equal to mgh (force times distance, remember). This is the amount of energy that is being 'stored' in the object and is therefore the amount that would be released if the object is dropped and allowed to fall through the distance h. If the object's entire store of potential energy is allowed to be converted into kinetic energy (by allowing the object to fall the full distance h back to its starting point) then the kinetic energy it will have at that point is

$$E_K = \frac{1}{2}mv^2 = mgh \tag{3}$$

from which we can deduce its velocity as

$$v = \sqrt{2gh} \tag{4}$$

which, by the way, is independent of the mass, so Galileo was right after all: all objects fall at the same rate.

A constant force like gravity near the Earth's surface is a particularly easy example since we can find the amount of work done against the force by simple multiplication. Most real forces, of course, aren't as cooperative, and vary with distance. This means that we need to use calculus to find the amount of work done, and thus the potential energy stored, when we move a mass around in such force fields. However, the principle is the same: find the amount of work that is needed to move the mass from point A to point B and the result is the potential energy stored in the mass. When the mass is released, the potential energy will be converted to kinetic energy (or released in some other way if the object is not totally free to move under the influence of the force) if and when it gets back to point A.

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