Chapter 3

The text does a nice job of explaining work and energy so be sure to read it carefully. There are fewer equations and more concepts in this chapter.

I will go over the chapter in class with some demonstrations and then do more demonstrations in the lab, including an explosion of hydrogen and oxygen gases that we will have generated from water using electricity.

Be sure to notice that the idea of mechanical work in physics is not the same as in ordinary conversation. If a weightlifter lifts 100 kg from the floor to 2.5 m height, work is done in both the physics and ordinary sense, but if the weightlifter **holds** that weight **without raising it further or lowering it**, no additional physics work is done! A great deal of biological energy is required to keep the weight at 2.5 m, but no physics work! From the physics point of view, it is just as if the weightlifter placed the weight on a 2.5-m high support and walked away. **When the weightlifter lowers the weight back to the ground, physics calculations say that the weight lifter does a negative work so that when the weight is back on the ground, no net mechanical work has been done!** A lot of food energy has, however, been converted to heat.

Also, note that **total energy is always transferred from one form to another; it is not lost or gained, just converted between different forms of energy – mechanical, electrical, nuclear, heat, light, sound, etc.** When you explain this to a student, you may be asked "Where did the energy come from in the first place?" Your best answer is "We don't know." You can talk about the Big Bang creation of the universe, but where did *that* energy come from. Physics tells a great deal about nature, but not everything. It tells us about things we can test using observations and experiments, but there will always be questions we cannot answer … yet.

Finally, **many calculations can be done using Newton's 2nd Law (F=ma) and forces, but it is often much easier to use the Conservation of Momentum and Conservation of Energy principles to get the same answers.**

The SI unit for work and energy is the joule (J), but many other units are in use. In particular, chemists traditional use the unit calorie (cal, **1 cal = 4.186 J**). Nutritionists also use the word "calorie" when they really are speaking of kilo-calories (kcal). **One "calorie" on a food package label is actually 1 kcal = 1000 cal.**

A 100 kg person climbing up a trail that rises 1000 m is doing work to gain gravitational energy:

$$\text{work} = \text{upward force} \cdot \text{upward distance} = \text{weight} \cdot \text{height}$$

$$W = m\,g\,h = (100\,\text{kg}) \cdot (9.8\,\text{m/s}^2) \cdot (1000\,\text{m}) = 9.8 \times 10^5\,\text{J} = 980\,\text{kJ}$$

Converting to calories, this is $(9.8 \times 10^5\,\text{J}) \cdot \left(\frac{1\,\text{cal}}{4.186\,\text{J}}\right) = 2.34 \times 10^5\,\text{cal} = 234\,\text{kcal}$.

This is only 234 food calories!!! Far more calories, maybe 5x as much, are expended by the biological processes used to keep the person alive and to operate and repair muscles.

Just lounging around, we burn about 1500 food calories each day. That is about 6.3 MJ/day. (1500 food calories = 1500 kcal = 6279 kJ = 6.279 MJ). Power is energy expended divided by time and has the watt (W) as its SI unit. Since there are 86400 seconds in a day, 6.3 MJ/day = 73 J/s = 73 W. Think of a continuously-lit 75 W light bulb. 25 students in a classroom heat the room about as much as a $(25\,\text{students}) \times (73\,\text{W/student}) = 1825\,\text{W}$ heater.

Hibernating animals lower their body temperature and therefore their base energy consumption so that their fat is sufficient to sustain their essential biological activity through the winter.

Work, Torque, and Mechanical Machines

Both work and torque are a force multiplied by a distance. Strictly speaking, they both have units of $\mathrm{kg \cdot m^2/s^2 = N \cdot m = J}$, but it is considered correct to talk of work as having units of joules (J) and torque of having units of newton-meter $(\mathrm{N \cdot m})$. For work, the force and distance are aligned in the same direction whereas in torque, they are perpendicular; work involves a change in energy and torque describes a twisting force around some pivot point.

Work

When you lift an object of mass *m* a distance *h* against gravity, your force on the object is upward and the object moves upward. You do a positive work equal to $W_{\text{done by you}} = m g h$.

At the same time gravity pulls downward on the object as it is moved upward. Gravity does a negative work $W_{\text{done by gravity}} = m g(-h) = -m g h$. In both these cases, the distance moved and the force direction are parallel; the full amount of the force contributes to the work.

When the object is lowered, you do a negative work and gravity does a positive work. Once back on the ground, no net work has been done by you or by gravity.

When a satellite moves around the earth in a circular orbit, there is no change in distance between it and the center of the earth, so no work is done and there is no change in the satellite's energy.

Torque

Torque is a measure of a twisting force around a pivot point. Consider two kids on a teeter-totter, one on the left side of mass m_{left} sitting at a distance of d_{left} from the pivot point, and the other on the right side of mass m_{right} sitting at a distance d_{right}. The weight of the left kid is pushing down on the left side causing a twisting force (torque) on the teeter-totter board in the counter-clockwise direction. The weight of the right kid is pushing down on the right side causing a clockwise torque. Typically, they will adjust their distances from the pivot point to balance. The twisting forces (torques) are then balanced. Here is the equation that then holds:

counter-clockwise torque = clockwise torque

$$m_{\text{left}} g\, d_{\text{left}} = m_{\text{right}} g\, d_{\text{right}}$$

Using $F_{\text{left}} = m_{\text{left}} g$ and $F_{\text{right}} = m_{\text{right}} g$, this becomes

$$F_{\text{left}} d_{\text{left}} = F_{\text{right}} d_{\text{right}} \quad \text{or} \quad \frac{F_{\text{left}}}{F_{\text{right}}} = \frac{d_{\text{right}}}{d_{\text{left}}}$$

which shows how the forces are different in a teeter-totter when the distances are different.

As they teeter and totter, the height change of the kids Δh_{left} and Δh_{right} are related to their distances from the pivot point since similar triangles are formed by the tilt angle, the distances, and the height changes:

$$\frac{\Delta h_{\text{left}}}{d_{\text{left}}} = \frac{\Delta h_{\text{right}}}{d_{\text{right}}} \quad \text{or} \quad \frac{d_{\text{right}}}{d_{\text{left}}} = \frac{\Delta h_{\text{right}}}{\Delta h_{\text{left}}}$$

Combining this fact with the force formula, we can obtain a general result that the work done at the left side W_{left} equals the work done at the right side W_{right}:

$$\frac{F_{\text{left}}}{F_{\text{right}}} = \frac{\Delta h_{\text{right}}}{\Delta h_{\text{left}}} \quad \text{or} \quad F_{\text{left}} \Delta h_{\text{left}} = F_{\text{right}} \Delta h_{\text{right}} \quad \text{or} \quad W_{\text{left}} = W_{\text{right}}$$

This is the principle of the lever used in crowbars, pliers, screw drivers, and assorted other hand tools. A similar analysis explains how wedges, knives, pins, screw threads, and slopes allow less force to accomplish a task. In all cases, however, the smaller force must be applied for a greater distance so that force multiplied by distance is constant; the same work is required.