**Metabolic Engines**

Now want to explore how our heat engine analysis can be applied to animal metabolisms in general, and humans in particular.

At the most basic level, an engine:

1. derives energy from a heat source
2. converts some of it to work, with efficiency η
3. exports the rest of the heat to the environment

And animals/people go through a similar process, with one major difference

1. derives energy from a *food* source
2. converts some of it to work, with efficiency η
3. exports the heat byproduct to the environment

Both heat engines and metabolic engines are described by the first law:



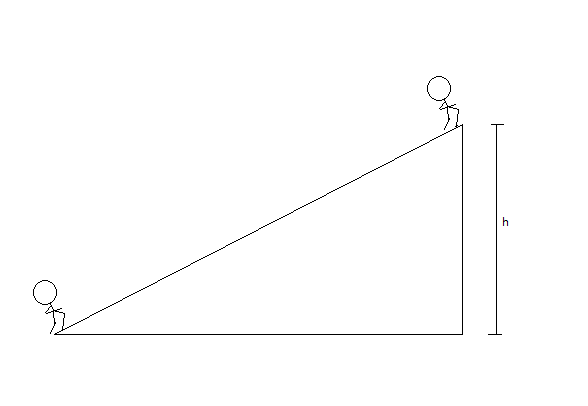
We can model the biomechanics of humans, adequately enough for our purposes, if we express the internal energy as:



KEint is of course the internal kinetic energy of all the atoms in your body and can be modelled, as it is for other substances, as KEint. = mcVT, where where m is your mass, cV your constant-volume heat capacity (about 3.5 kJ/kg∙C), and T your temperature. PEchem. is just a generic term used to represent the internal chemical potential energy stored in, say, ATP molecules whose energy can be unleashed to perform work or change your mechanical energy. And this can be modelled as PEchem. = uN, where u is the energy contained in each ATP molecule, and N is the number of such molecules, but we generally won’t bother. So we’ll just write:



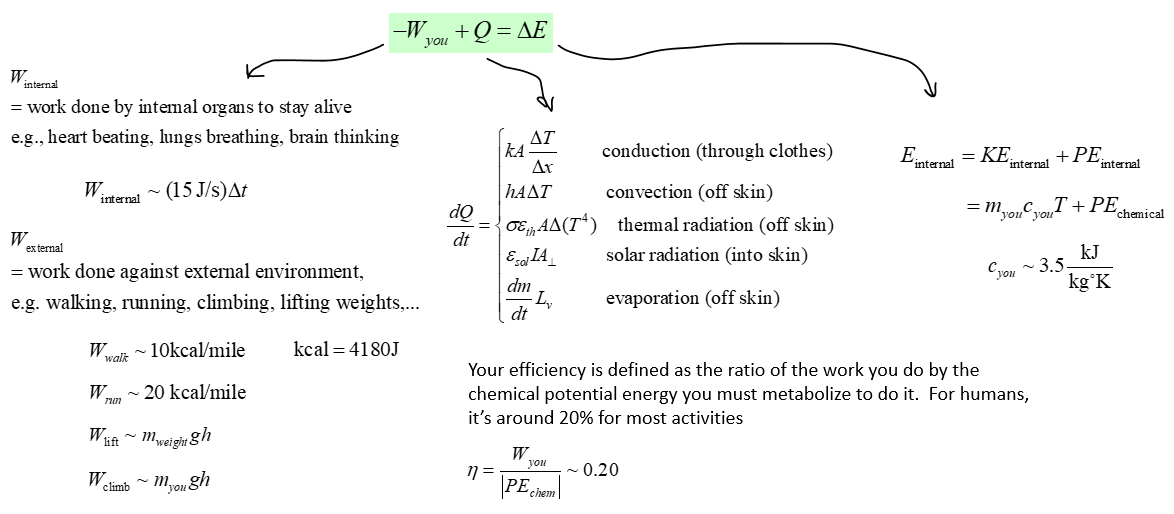
A human body functions much like a heat engine to convert energy into work. For instance, just to maintain basic body functions, you break bonds in ATP molecules releasing internal chemical potential energy (the analogue to input heat for a heat engine). Some of this energy is delivered to muscles like your heart or chest to do what I’ll call *internal work*, in the form of circulating blood or to enabling you to breathe. It will also be delivered to your arms and legs if you are doing *external ‘work’* in the sense of pushing yourself up an incline, or *actual external* work in the sense of lifting a weight. The rest of this energy gets wasted as internal kinetic energy – i.e., you get hotter (the analogue of a heat engine’s output heat).

The efficiency of this process is defined to be the ratio of the work output to internal chemical potential energy input:



Typical human efficiency ranges between η = 20% to 25%. In the mountain example, your ‘work’ would be equal to your change in mechanical energy, i.e. Wext. = ΔKE + ΔPEg = 0 + mgh, assuming you didn’t speed up as you climb the mountain (an unlikely proposition). A similar analysis applies to lifting weights, Wext. = mgh, where m is the mass of the weight. We could calculate the amount of work required to run as well. If we treat it as hopping along the ground then for typical masses and such we would arrive at an estimate of Wext. = 20kcal/mile. Walking, similarly, works out to about Wext. = 10kcal/mile. It would be more difficult to ascertain how much internal work your heart and chest, etc., do just to keep you alive. But we can figure it out indirectly. A typical human needs on the order of 1500 kcal to maintain bodily functions. This would be ΔPEchem, and so W­int = (1500 kcal)η ≈ 300 kcal over the course of a day, which works out to about 15 J/s. So we could say that internal work, over a time interval Δt is approximately Wint. = 15Δt. So the first law would take the following form in most cases of interest:



Let’s do some examples.

**Example**

Suppose you (m = 65kg) jump up into the air 50cm once every 2s. How long would it take to burn 500 Cal? Ignore internal work.

So ΔPEint = 500Cal = 500×4184J = 2.09×106J. And we need to figure out how long we have to keep jumping to burn this many calories. Well, every jump requires an amount of work equal to W = mgh = (65)(9.8)(0.5) = 318 J. You make a jump every 2s, and so the total amount of work you do in a given time *t* is (in Joules): W = (318)(t/2) = 159t. Now the relationship between W and ΔPEint is given by the efficiency, η = W/|ΔPEint|. So we have:



**Example**

Suppose you run 6 miles. Approximately how many calories do you burn? How much heat do you generate? If you dissipate this heat through evaporation of water (sweat), how much would you sweat during the 6 mile run (in kg)? Ignore internal work.

We’ll use the 1st law. During the 6 mile run you do about 20kcal of work per mile. So that’s W 6×20kcal = 120kcal = 120×4184J = 5×105J of work all total. And using the efficiency, we can ascertain the amount of internal chemical potential energy burned.



Now we can use the 1st law to work out how heat we give off. We’ll assume that our temperature is not changing. And remember that ΔPEint is *negative* because we have burned off that energy.



So you generate about 2MJ of heat. This heat, if allowed to stay inside you would raise your temperature according to whatever your body’s heat capacity is. And it would probably raise it enough to kill you. So instead you body has evolved a mechanism to dispose of this heat via evaporation. So if all of this heat goes into evaporating water, then the mass of water required would be:



So you’d evaporate about 0.89kg of water, which amounts to around 2 lbs. This is the main reason you weigh so much less after a run. Unfortunately, you haven’t burned 2 lbs. of *fat*.