EFB 462/662 Animal Physiology: Environmental & Ecological
The Laws of Thermodynamics

Thermodynamics is concerned with the relationships between energy, heat and work. It has its origins in the empirical problem of how to make engines work efficiently, and most of classical thermodynamics was fleshed out during the Age of Steam. This is why many of its units and concepts (the joule, the watt, the kelvin, Carnot cycle) are named after the engineers and physicists that made steam power a practical tool.

It turns out, though, that the rules governing the efficient design of steam engines also govern any system that does work of any sort, which includes living things. For example, one can measure the work done by a steam engine as a function of the fuel energy put into it. One can do the same for an organism "engine," consuming fuel and doing work, like a mill powered by a harnessed horse fed with hay. Interestingly, the work done by both engines will be constrained in some similar and rather fundamental ways, suggesting that the two are governed by the same laws. Indeed, one of the earliest indications that this might be so came from a study of the energy costs of boring cannon barrels and comparing them when the work was done by a steam engine against the same work powered by a horse. Irrespective of whether the fuel was coal or oats, or whether the engine was steam power or horse power, the energy cost of boring a cannon barrel was very similar. This similarity means that thermodynamics is at the center of understanding how organisms work, and even how they are able to exist at all.

Thermodynamics has as its foundation three laws, numbered First, Second and Third. All concern the behavior of a *universe*, composed of a *system* and its *surroundings*. These terms can be rather slippery, and being careless about what these are can make some very simple ideas seem very difficult. For example, the thermodynamic universe can encompass something as small as a molecule, a cell, or an organism, rather than everything, as the common meaning of the term implies.

The *First Law of Thermodynamics* constrains the total quantity of energy in the universe, and is sometimes designated as the law of conservation of energy. It simply states that the total amount of energy in the universe is a constant. It does not constrain the energy from being either in the system, or the surroundings, only that their sum must be constant. It also does not constrain the form the energy can take (that is, it can be potential or kinetic energy, heat energy, electrical energy), nor does it constrain the flow of energy between the system and its surroundings.

The *Second Law of Thermodynamics* is sometimes known as the law of increasing entropy. This simple law has some marvelously subtle implications for life. The Second Law states that whenever energy does work, whether it is the system doing work on the surroundings, or vice versa, some fraction of the energy is lost to random molecular motion, or entropy. Thus, in any universe where there is work being done, either by the system on its surroundings or vice versa, there will be a relentless increase in the universe's entropy. Importantly, the Second Law does not force increase of entropy on either the system or the surroundings. Likewise, there is nothing in the Second Law that prevents an ordering of either. However, any decrease in the entropy of one must be accompanied by a greater increase in the entropy of the other so that the universe experiences a net increase of entropy. Thus, organisms, which can be thought of as transient "pools" of low entropy, exist only by disordering the universe in which they exist.

The *Third Law of Thermodynamics* is a bit more esoteric, but it is important in that it gives us a thermodynamic definition of temperature. Put simply, it states that there is a lower limit on the temperature of any universe, where random molecular motion, or heat, falls to zero. This is the basis of the absolute, or thermodynamic scale of temperature, designated by units of kelvins, or K. The zero on the absolute temperature scale is often referred to as the absolute zero, because a temperature lower than 0 K is impossible (there is no such thing as negative motion). Compared to more frequently used temperature scales like the Celsius or Fahrenheit scales, which are zeroed at "convenient" temperatures, the absolute zero is -273.15^{o}C, or -459.67^{o}F.

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