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Understanding the Thermodynamics of Biological Order

RECOMMENDED FOR AP Biology

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Abstract

By growth in size and complexity (i.e., changing from more probable to less probable states), plants and animals appear to defy the second law of thermodynamics. The usual explanation describes the input of nutrient and sunlight energy into open thermodynamic systems. However, energy input alone does not address the ability to organize and create complex structures or explain life cycles – in particular, growth regulation and dying in the presence of adequate nutrients. Understanding the roles of macromolecules such as DNA, with their apparent information-processing capability, affords opportunity to understand biological order.

Key Words: *Biological order; second law; DNA; open system.*

○ The Second Law of Thermodynamics & Life

Plants and animals defy the universally observed tendency to decay, decline, and disintegrate by their own growth in size, complexity, and organization and by creating uniquely ordered structures. The tendency toward disorder is the basis of the second law of thermodynamics. One biology textbook presents this important question: “Humans, indeed all living things, are highly ordered combinations of organic substances. Is this a violation of the second law?” (Pruitt & Underwood, 2006). Another puts it this way:

The tendency toward disorder is the basis of the second law of thermodynamics.

> A sprouting plant is constantly building itself up; it is making larger, more complex molecules (proteins, starches) from smaller, simpler ones (amino acids, simple sugars). This increasing organization stands in contrast to the spontaneous course of things – breakdown and disorder – and thus may seem to be a violation of the second law. (Krogh, 2009)

And another: “According to the second law of thermodynamics, energy transformations result in the universe becoming more disordered. How, then, can we account for biological order?” (Campbell et al., 2009).

The effect of the second law is instructively portrayed by showing photographs of a teenager’s desk area becoming disarrayed in time with use (Figure 1).

○ Disorder as Entropy

Although the second law can be described in terms of energy macroscopically, the fundamental understanding of the second law at the molecular level was formulated by Boltzmann (1844–1906). The measure of disorder, entropy (S) is defined in terms of the number of microstates or probability (W), and k is a constant:

$$S = k \ln W$$

Increases in disorder (i.e., in entropy) are associated with the change from a less probable to a more probable state (Van Wylen et al., 1994). The teenager’s area is likely to be disarrayed, a more probable state because there are many more possibilities than with a neat and tidy room. Restoration of an orderly room from disarray without intervention is improbable. The positioning of items in their appropriate places requires information and use of that information, as by the parent, to bring about order (Figure 2).

○ Incomplete Explanation

Energy input into biological systems that are thermodynamically open is the premise of the usual explanation given for the existence of order (Figure 3):

> The answer is that a cell is not an isolated system: it takes in energy from its environment in the form of food, or as photons from the sun…and it then uses this energy to generate order within itself. In the course of the chemical reactions that generate order, the cell converts part of the energy it uses into heat. The heat is discharged into the cell’s environment and disorders it, so the total entropy – that of the cell plus its surroundings – increases, as demanded by the laws of physics. (Alberts et al., 2008)

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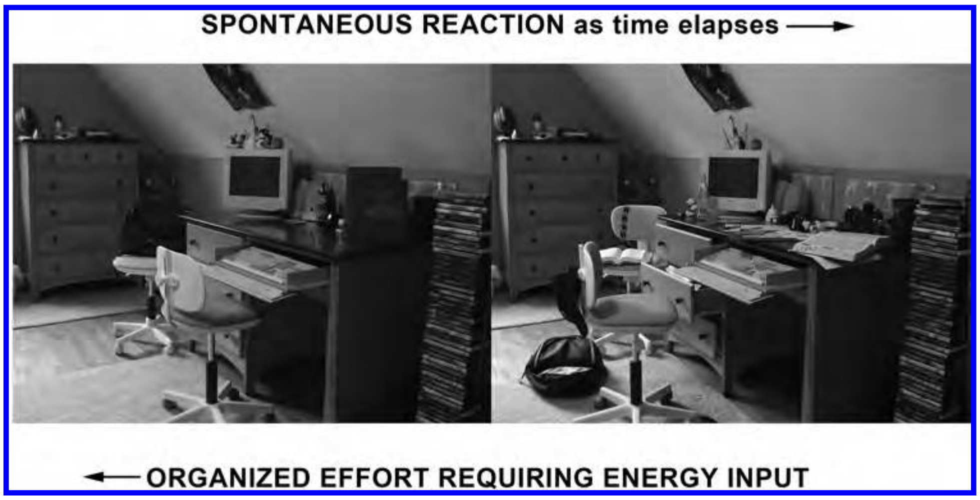

Figure 1. "An everyday illustration of the spontaneous drive toward disorder" (similar to Alberts et al., 2008).

Figure 2. Parent bringing about order by employing information to direct and organize effort (energy).

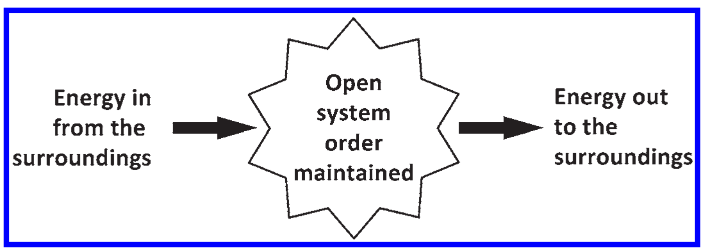

Figure 3. Illustration relating energy to order in an open biological system (based on a figure in Raven et al., 2005).

Historically, the inconsistency of the second law and living systems was addressed by Nobel Laureate Erwin Schrödinger in his 1944 book *What is Life?* "How does the living organism avoid decay? The obvious answer is: By eating, drinking, breathing and (in the case of plants) assimilating" (Schrödinger, 1992). Nutrient and sunlight energies are necessary to enable biological order without violating the laws of thermodynamics. However, energy considerations alone do not account for biological order. This can be seen in Figures 1 and 2. The considerable, but randomly focused, energy of a 3-year-old child would not restore order in the room.

○ The Role of DNA

Boltzmann's view of the second law brings into focus the necessity for an organizing activity that moves from less ordered, more probable, higher-entropy states to less probable arrangements of lower entropy. For example, the formation of a unique DNA molecule out of as many as $4^{3,000,000,000}$ possible arrangements of nucleotides is highly improbable and requires more than a supply of energy. The double-helix template reproduction is the mechanism necessary to overcome the universal tendency toward randomness.

On the microscopic cellular level, biological functions are known to be directed and controlled by macromolecules, such as DNA, and by the proteins, enzymes, and other structures that develop from them. At the visible macroscopic level, as an example, spiders inherit the ability to spin elaborate web structures; it is unlikely for those capabilities to be reinvented or learned by each generation. There is no reason, therefore, to assume that the mechanism operative at the microscopic level is not also controlling and directing the creation of the unique and complex biological structures that are seen. The deduction is that DNA is the prime cause or source of biological order and the resolution of the paradox posed by the second law of thermodynamics.

Macromolecules such as DNA determine the complete life cycle, birth, growth, maturity, decline, and death of the organism. The biological clock progresses as irreversibly as time's arrow, as is expected from the second law. Growth in size and complexity occurs from birth to maturity, with nutrients indeed being a necessary factor. However, growth rate and attained height in humans, for instance, are regulated by genetics. If nutrition alone could induce height growth, there would be a surfeit of 7- or 8-foot athletes playing basketball. At some point, organisms normally decline and die even while remaining in environments that contain sufficient food to sustain their life. An adequate nutrient (energy) supply does not ultimately prevent naturally occurring decline and death. The operative or causal influence cannot be nutrients external to the open systems. The controlling factor must be internal and capable of recognizing time or sequencing.

There is the insight that the linear sequence of nucleotides in DNA is intense in information, with a duplicate set of instructions, an algorithm, for creating and maintaining each cell and the whole organism – in essence, software (Nelson, 2004; Karp, 2010). Information-processing capability in DNA provides a viable explanation for the complicated mechanisms observed. This idea is illustrated by the parent bringing about order by employing information to direct effort (energy) in Figure 2.

In thermodynamics there is a famous thought experiment that is relevant and prompts the question: Does DNA act as a modern-day "Maxwell's demon" (Smith, 2010), that is, as a nano-robot programmed to

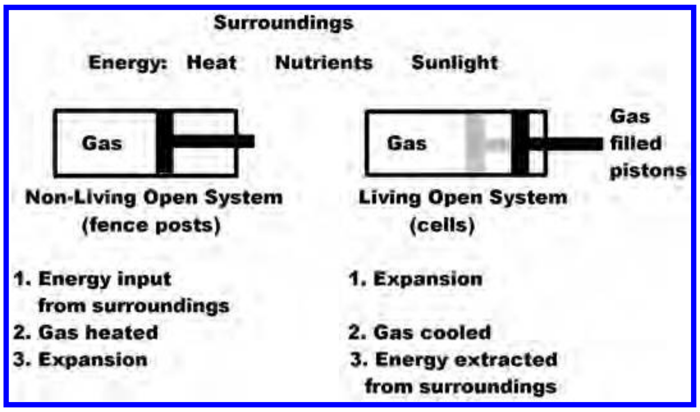

Figure 4. Model contrasting nonliving and living open thermodynamic systems.

generate and maintain particular structures and processes in its system, using information and energy to lower entropy, for a period of time? (Dolev & Elitzur, 1998). Realization of the role of DNA beyond initiation of life's chemistry advances the understanding of biological order and at the same time presents interesting avenues for exploration.

○ Open-System Clarification

There is a subtle but significant difference between biological and non-living open (not isolated) systems (Figure 4). For example, a fence post is an open system. A metal post will thermally expand when warmed by external factors (sunlight or ambient air) but retains its structure and does not grow in complexity. Using a model to represent the two cases, it is seen that biological open systems behave as if internally controlled, not reacting to external variables in the way that nonliving systems do. Cells and organisms act upon their surroundings, even foraging, taking in and rejecting nutrients, controlling quantity and variety. Some internal mechanism suggestive of information processing seems to be in control.

○ Conclusions

The ability of organisms to grow complex structures, opposing the universal, natural tendency toward disorder, points to the operation of macromolecules such as DNA and their encoded information. Without a description of the role of DNA, textbook explanations of the necessary intake of energy by organisms as open systems are not adequate to account for change from more to less probable states, counteracting the second law of thermodynamics. Life cycles, the ability to create complex structures and thermodynamic analysis of open systems, indicate an internal mechanism. Focusing on DNA and the other macromolecules of living systems with apparent information-processing capability affords an opportunity to understand the order and complexity in living entities and the structures they create.

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