A biologist's musing on teaching about entropy and energy: towards a better understanding of life processes

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ABSTRACT Should entropy and energy be emphasised as relevant concepts for biology education? This question will be discussed, highlighting the ways in which the concepts of entropy and energy can contribute to a better understanding of biological processes. Organisms are open systems. Therefore, the chosen perspective is different from the traditional viewpoint, which is mainly dealing with closed systems. Based on this standpoint, dynamic conceptions for teaching about energy and entropy in biology education can be formulated.

What is entropy?

The ability to form and maintain structures, that is, order, is a remarkable characteristic of living systems. To understand these processes and teach about the role of energy in this context, one necessarily has to deal with the concept of entropy. This was illustrated by the physicist Erwin Schrödinger in 1944 in his famous, easily understandable little book *What is Life?* With it, he cleared up the misconception that the answer to the question '*How does the living organism avoid decay?*' could be by the absorption of matter or energy. Instead, Schrödinger elaborates:

> *That the exchange of material should be the essential thing is absurd. Any atom of nitrogen, oxygen, sulfur, etc., is as good as any other of its kind; what could be gained by exchanging them? For a while in the past our curiosity was silenced by being told that we feed upon energy. … Needless to say, taken literally, this is just as absurd. For an adult organism the energy content is as stationary as the material content. Since, surely, any calorie is worth as much as any other calorie, one cannot see how a mere exchange could help. … Thus the device by which an organism maintains itself stationary at a fairly high level of orderliness.… really consists of continually sucking orderliness from its environment.*

However, there is more to this process than only the absorption of order. Removing the continually arising disorder from the body is essential:

> *Energy is needed to replace not only the mechanical energy of our bodily exertions, but also the heat we continually give off to the environment. And that we give off heat is not accidental, but essential. For this is precisely the manner in which we dispose of the surplus entropy we continually produce in our physical life process.*

Schrödinger's argument is based on the law of physics stating that during processes in a closed system, entropy steadily increases. Here, entropy is no mysterious, order-destroying power of chaos, but rather a physical unit (measured in joule/kelvin ($\mathrm{J\,K^{-1}}$)). Entropy is a directional measure which purports that processes spontaneously only work in one direction, namely the direction that causes the number of possible states of the particles involved in the processes to increase (second law of thermodynamics). A metaphor for entropy is 'disorder'. As metaphors do, this term illuminates one aspect of entropy while it obscures others. The everyday understanding of disorder corresponds with entropy in so far as the observed particles can occupy multiple locations in space. Disorder describes the number of possible different states of the particles. Accordingly, order means that every particle has its designated place. However, contrary to the everyday understanding of the term entropy as meaning disorder, it also refers to a

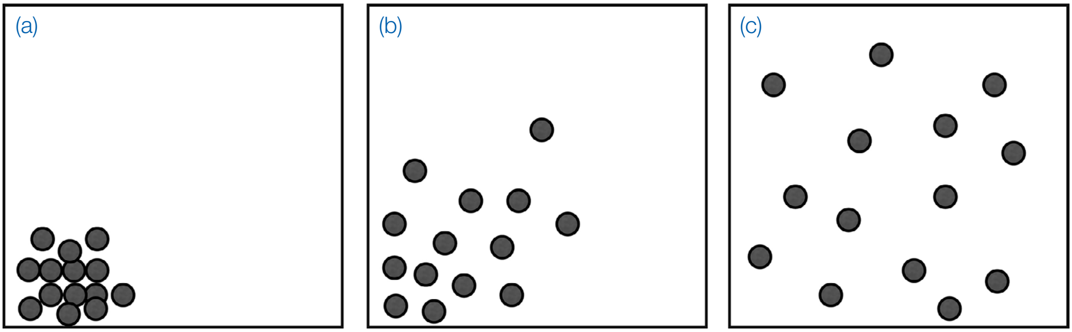

Figure 1 Diffusion of a portion of gas: the distribution in the available space tends to become uniform

uniform distribution of the observed particles in space, while order means unequal distribution. A prime example for an increase of entropy is the diffusion of a gaseous or dissolved substance.

The thermal movement of the particles statistically leads to a uniform distribution in space, which means that every molecule can occupy more locations in space than before. In Figure 1, entropy (disorder) increases from state (a) to state (b) and from state (b) to state (c).

Thus, within a system, entropy can increase in different ways:

- by expanding the system's size, if by doing so the particles can occupy more possible locations than before;
- by raising the temperature (by supplying energy), as the particles can adopt more different states within a unit of time than before because of their increased thermal movement;
- by increasing the number of particles in a system (e.g. by breaking down macromolecules into smaller molecules).

The opposite of entropy (the opposite reciprocal variable) is known as *negentropy* and is paraphrased as order, or difference, or structure. In Figure 1, negentropy decreases from state (a) to state (c). In terms of entropy and negentropy, equal (uniform) distribution means disorder, while unequal distribution means order and structure.

It should be noted that the metaphors of the positively coined technical term of entropy have negative connotations ('disorder', 'lack of structure'), while the negatively coined term *neg*entropy has positive connotations ('order', 'structure'). Entropy gives processes direction. This also means that opposed processes, such as structural formation within a system, can only happen if simultaneously entropy increases elsewhere. Only such entropically open systems allow for structural formation, which, as Schrödinger puts it, 'absorbs' negentropy and 'dispenses with' entropy.

Open systems

Schrödinger's claims presuppose open systems. These can be categorised into materially open systems (intake and output of matter), energetically open systems (intake and output of energy) and *entropically open systems*. The last of these can be characterised by an intake of energy or matter of higher order (lower entropy) and output of energy or matter of lower order (higher entropy). In living organisms, this applies to taking in materials such as high-ordered proteins and excreting simple materials such as carbon dioxide and water, thereby increasing entropy in the environment. It applies also to the intake of energy, for example of radiation from the Sun by photosynthetic organisms, or the intake of chemically stored energy, through the system of nutrients and oxygen, by heterotrophic organisms, as well as to the output of heat by all organisms. This means that in an entropically open system, entropy can decrease (structure formation), while inevitably increasing in a closed system. Formally, a system becomes a closed system, if one includes the surroundings of the open system in the observation. Ultimately, only the universe is a closed system (Figure 1). Therefore, if entropy decreases because of structure formation, as it does in organisms, somewhere within the universe, entropy must increase, for example in the Sun. In fact, entropy in the Sun constantly increases, while capturing solar radiation and radiating heat makes it decrease on Earth.

Figure 2 illustrates diagrammatically an entropically open system.

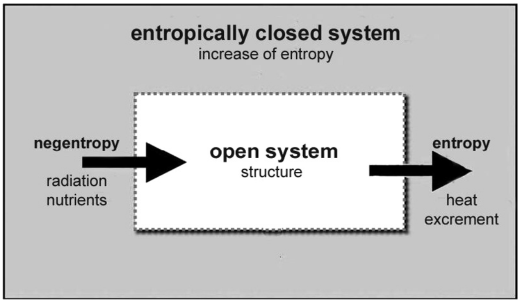

Figure 2 Flow of entropy in an open system (adapted from Larsen, Groß and Bogner, 2015)

In an entropically open system, structure formation indicates the decrease of entropy, while in an entropically closed system entropy increases. The decrease of entropy within the system is managed by the input of entropically low energy or materials (negentropy) and the output of materials of high entropy such as faeces, carbon dioxide, water or the output of energy of high entropy as heat.

The importance of the removal of entropy for structure formation can be demonstrated using crystallisation in a glass beaker (Figure 3). Crystallisation causes an increase in order (structure formation) and therefore a decrease in entropy. Does this decrease of entropy within the beaker conflict with the second law of thermodynamics, that is, the increase of entropy in all processes? The beaker is an energetically open system: during the process of crystallisation, energy is released into the area surrounding the beaker (heat of crystallisation). Therefore, the glass beaker is also an entropically open system, to which the second law is not applicable. If, however, one was to observe both the beaker and its surroundings, that is the entropically closed system, one would find an increase in entropy: heat increases the disorder in the surrounding area.

Without an understanding of entropy, it is impossible to explain structure formation in open systems. The occasionally stated claim that the existence of living creatures contradicts the second law of thermodynamics mistakes these organisms for entropically closed systems. Following this misjudgement, exemptions are made for the emergence and existence of life. Therefore, entropy and negentropy are central terms in biology, if one is to understand the conditions of structure formation in organisms without vitalist assumptions (such as the idea of a special life force to explain the difference between living beings and the inanimate).

Structure formation is inevitably connected to the flow of heat out of a system, living as well as inanimate. Even though thermal energy is used by homeothermic organisms to sustain body temperature, from a biological point of view the flow of heat out of living organisms can be considered a rather useful 'entropic waste removal' process. Thus, Schrödinger radically reassesses the usual (physical) view of the devaluation of energy (because it remains

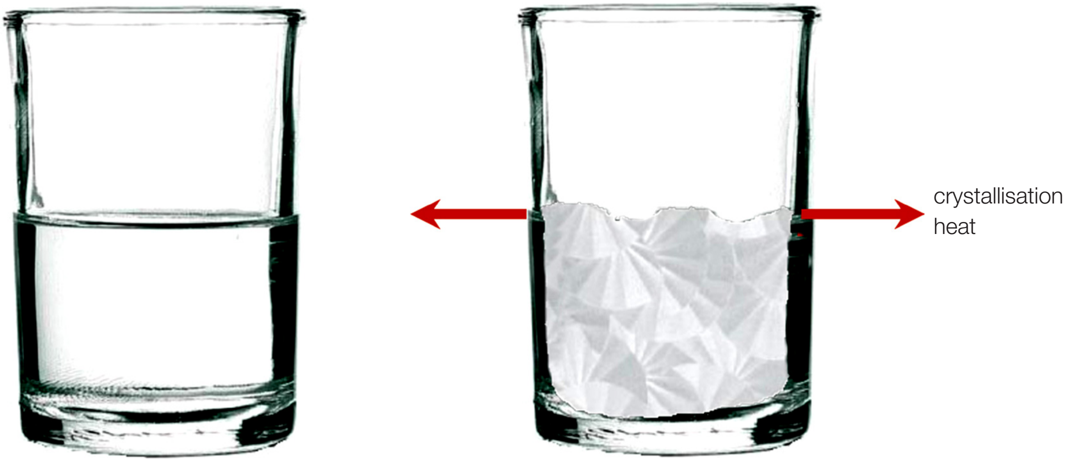

Figure 3 Crystallisation of water in a glass beaker, with arrows indicating flow of energy and entropy out of the system (crystallisation heat)

applicable only with limitations) with regards to living creatures: heat is the transfer of entropy (disorder) to the environment, in order for the structure of an organism to be built and persist in the face of the de facto increase of entropy.

The effect of the export of entropy by heat can be demonstrated with the flame of a candle (Figure 4). In the flame, energy is constantly transferred by the reaction of wax with oxygen. Heat is transferred from the flame into the surrounding area (dissipation). Because heat is transported out of the flame, entropy decreases in the flame. The structure of the flame, with its several zones, builds and preserves itself while the particles are changing (dissipative structure). The flame is thus a simple analogue of an organism.

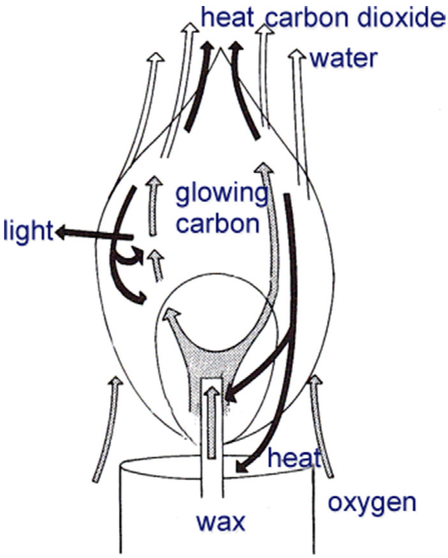

Figure 4 Candle flame: black arrows represent flow of energy, grey arrows the flow of substances with fuel value, and light arrows the flow of substances without fuel value

Dissipation: a common feature of entropy and energy

As the example of disposal of entropy through heat has shown, there is a close connection between energy and entropy. It is a property of energy that it diffuses. This process is called dissipation. The French chemist Ilja Prigogine calls both flames and organisms *dissipative structures*. This is a suitable term because heat flow (dissipation) is closely connected to structure formation. Furthermore, dissipation (or dispersion) of energy allows for a close relationship of entropy and energy: entropy is a measure of the dispersion of energy in space. Accordingly, the second law of thermodynamics can be phrased as: '*Energy spreads out spontaneously if not hindered from doing so*' (Wei *et al*., 2014: 319).

The two definitions of entropy (disorder and dissipation of energy) can be combined: energy becomes disorderly by dissipating; the disorderly energy is emitted from energetically open systems by means of heat flow (Figure 2). This creates a dynamic understanding of energy, which will be considered next.

Energy flow: exergonic and endergonic reactions

Biological processes are almost exclusively chemical processes; therefore, it is appropriate to employ a chemical view of the biological considerations regarding energy (Kattmann, 2015). In terms of energy, there are exergonic and endergonic reactions. Exergonic reactions occur spontaneously and, in the process, provide energy. Endergonic reactions do not occur spontaneously: they require energy input. The basis for an accurate understanding is that energy is not provided by splitting, but by bonding. No energy is stored in chemical bonds (Cooper and Klymkowsky, 2013). A common misunderstanding has to be revised: 'bond energy' does not refer to the energy used for bonding, but rather to the energy that is needed to split bonds; every splitting of chemical bonds requires energy and every creation of chemical bonds releases energy. Therefore, exergonic reactions are reactions in which the creation of products provides more energy than the splitting of source materials (reactants) requires. In other words, the reaction products in their entirety contain stronger chemical bonds than the reactants. It is the other way around for endergonic reactions.

Chemical reactions bring about the *energy flow* in metabolism; using energy means using the energy *flow*. Organisms use energy by linking endergonic reactions (e.g. biosynthesis) with exergonic reactions (e.g. hydrolysis of adenosine triphosphate, ATP). The energy is chemically provided by exergonic reactions, enabling endergonic reactions to occur. Biologists are used to referring to nutrients or ATP as 'energy-rich substances' (Quinn, 2014). This misrepresentation neglects the fact that energy is not stored in a substance but provided by a reaction in which multiple reactants – not just one substance – are needed.

ATP is not rich in energy. Accordingly, one should not teach that energy is provided by splitting ATP into adenosine diphosphate (ADP) + P. The splitting of ATP requires energy, as does any splitting of chemical bonds. The splitting of ATP is endergonic! The energy is provided by the reaction of ATP and water to ADP, phosphate and hydrogen ions (hydrolysis of ATP). Nutrients are also not energy-rich; their caloric value is the result of a reaction with oxygen (Ross, 1993; Needham, 2014). The role of oxygen is often forgotten or neglected because it is always present and invisible. To gain insight into this relationship, one should point out that humans, like other animals, need not only to eat but to breathe. For older children, this connection should be explained chemically in terms of cell respiration.

The absence of oxygen changes the energetic situation for organisms dramatically. It shows again that the energy is not stored in glucose, but rather that the use of energy is accounted for by the *reaction possibilities*. In the case of oxygen deficiency or exclusion, the exergonic reactions of glycolysis (or rather fermentation) take the place of oxygen respiration. However, they make less energy available. Lactic acid fermentation, for example, provides only one-tenth of the energy that cell respiration would otherwise make available.

The above also provides an explanation for how energy can be chemically retained.

Energy storage: chemical systems

Chemical energy storage systems are created by substances that (under certain circumstances) react exergonically with each other. Fuels, nutrients and biomass are not therefore, in isolation, energy carriers or energy storage systems. Energy carriers are the reactants of an exergonic reaction, not one of the partners alone: actual examples of energy carriers and energy storage are chemical systems such as the 'ATP–water' and the 'glucose–oxygen' systems.

There are, however, major chemical differences between these two systems. The 'ATP–water' system is unstable; because ATP reacts with water instantaneously, it only exists for a few seconds within a cell. The 'glucose–oxygen' system, on the other hand, is stable. Whether an energy storage system is stable or unstable depends on its required activation energy. The amount of activation energy in turn is directly related to the amount of energy required to split the chemical bonds of some molecules of the reactants (here glucose and oxygen). The activation energy of the exergonic reaction of glucose and oxygen is so high that glucose does not ignite at organismal temperatures in the presence of oxygen.

Energy flow and energy storage in biosystems

Crucial for the understanding of the use of energy in organisms is their nature as *energetically open systems*. The observation of open systems helps overcome some barriers to learning. Many learners think energy can be destroyed and matter can be easily turned into energy (Wilson *et al*., 2006). At the heart of these everyday ideas is the concept of the body as a vessel, in which energy is being created and consumed (Burger and Gerhardt, 2003). Accordingly, behind statements by students about energy being consumed or created by living creatures, there is the idea of an energetically closed system. This thinking can be countered by teaching that biosystems are systems of energetic flow. It is not enough to stress that energy is always contained and therefore cannot be created or destroyed. A merely negative declaration does not paint an accurate picture for learners. Instead, this can be provided to them by illustrating the absorption and emission of energy: the flow of energy through open systems indicates that energy is neither being produced nor consumed, but rather absorbed and emitted. Thus, there is a change of perspective from closed systems to open systems: ideas of production and consumption are abolished in favour of the processes of absorption (or intake) and emission (or excretion). This conceptual reconstruction leads to a scientifically accurate understanding (Figure 5). It can be illustrated by the examples of eating and breathing or, on a molecular level, by cell respiration in heterotrophic organisms, and by photosynthesis and cell respiration in photoautotroph organisms such as cyanobacteria and plants.

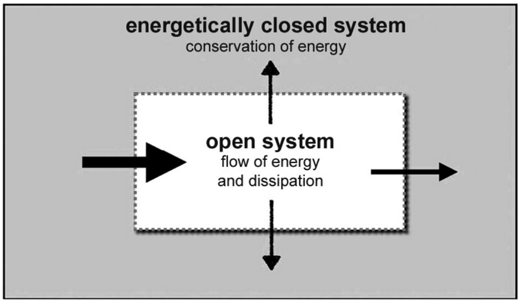

Figure 5 System of energetic flow. The arrows indicate the flow of energy: intake of energy (by radiation or nutrients) and emission of energy (by heat). The various directions of emission indicate the dissipation (adapted from Larsen, Groß and Bogner, 2015)

Use of energy in cells

When it comes to the metabolism of living things, we need to be aware that, occasionally, *material* and *energetic* aspects are improperly confused in everyday use, school textbooks and even in scientific accounts (Chabalengula, Sanders and Mumba, 2011; Lancor, 2014; Needham, 2014; Kattmann, 2015; Reimer and Pahl, 2016; Trauschke, 2016). In class, the two aspects should be clearly separated: in photosynthesis, glucose is not formed by light, but by carbon dioxide and water (material view). Accordingly, it has to be stressed that energy is not a material, and that material is not converted to energy, except in nuclear reactions.

An energetic view should deal with chemical reactions, not material properties. Light is not transformed into glucose. The energy of radiation is also not stored in glucose. Rather, the energy supplied by light causes (by means of photosynthesis) the splitting of water molecules. It is saved in the glucose–oxygen system (energetic view). The description of glucose as an 'energy carrier' or 'potential energy' mixes the material and energetic views improperly. Energy is supplied by the exergonic reaction of glucose and oxygen (or, in case of an exclusion or lack of oxygen, by other exergonic reactions).

Energy flow (energy transfer) and *energy storage* are fundamental processes in understanding energy conversion (Boohan, 2014; Millar, 2014). Thus, the processes of photosynthesis and cell respiration can be depicted as a sequence of energy flows, as well as short-term (unstable) and long-term (stable) energy storage: as storage–flow systems (Figure 6).

The following connections appear to be particularly important:

- In *photosynthesis*, sunlight is used for endergonic reactions to split water (photoreaction). Technically, this should create the unstable energy storage of the chemical system of hydrogen and oxygen. This would immediately combust in an oxyhydrogen reaction (exergonic reaction), which, however, is prevented by the separate transport of hydrogen ions and electrons.
- What follows is the creation of the *unstable energy storage* of hydrogen ion difference and of the chemical system ATP–water.
- The energy storage of ATP–water is unstable. If ATP could be stored over longer periods of time, the energy-intensive route via the creation of nutrients would be energetic waste.
- Only by synthesising glucose can *stable energy storage*, the glucose–oxygen system, be created. By means of its energy, ATP is created anew in cell respiration.
- During *cell respiration*, the water splitting of the photoreaction is reversed into the creation of water. In this way, the energy from the water-splitting process of the photoreaction, which has so far been stored, can be used. This energetic link between photosynthesis and cell respiration may give learners a meaningful insight into these fundamental physiological processes of life.

Central concepts for teaching biology

In physics lessons it has proved useful to highlight four central concepts of energy: energy conversion, energy conservation, energy transfer and energy degradation (Duit, 2014). While these concepts are maintained in the background, *the dynamic processes in open systems* are paramount in the context of biology. Accordingly, energy and entropy should be taught in three dynamic dimensions, all referring to the flow (Figure 7).

Figure 7 indicates the following aspects:

1. In principle, energy flow and mass transport must be distinguished.
2. Energy flow and energy storage. The physically central concept of energy conservation takes a backseat to the flow and storage of energy. Energy conversion and energy transfer

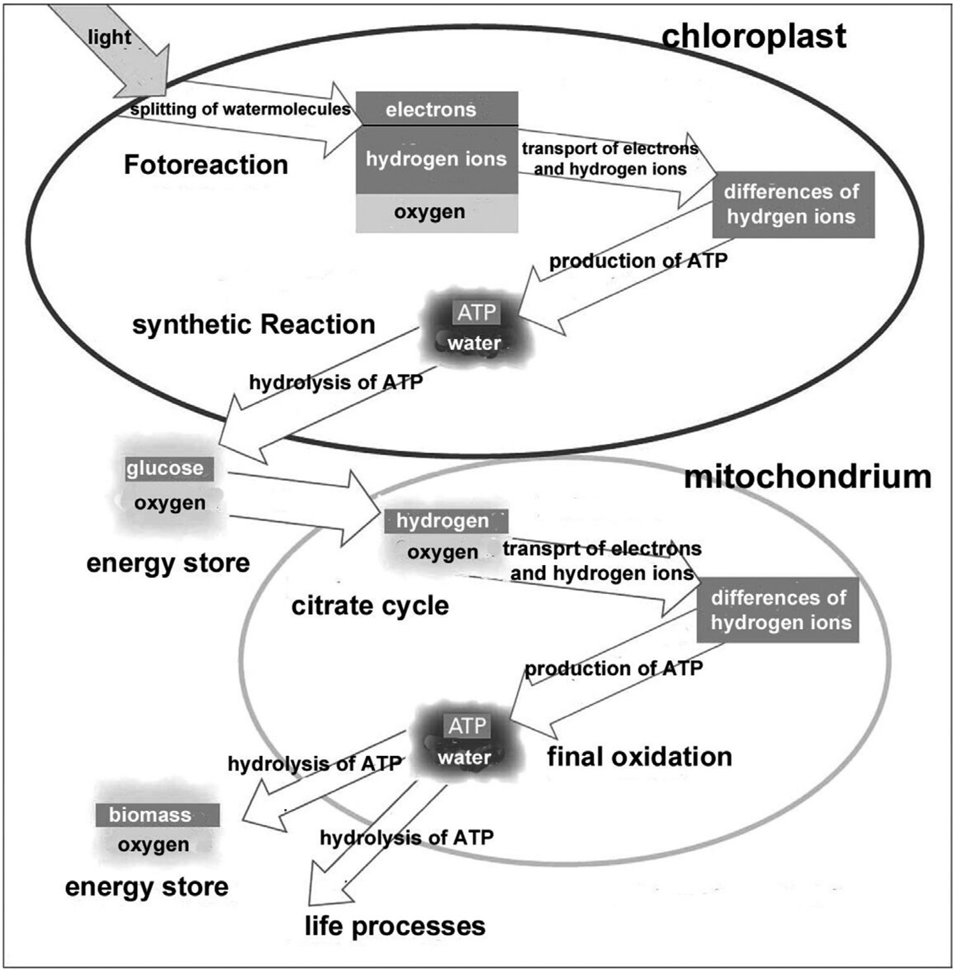

Figure 6 Energy flow through a plant cell during photosynthetic activity: arrows represent energy flow and boxes energy storage (the blurred outlines of some boxes indicate that the reactant is present in the surrounding area). The decrease of energy within the system because of waste heat is not included; waste heat is part of every process. Ultimately, the energy for life processes is emitted entirely by heat. The energy chemically stored in the biomass–oxygen system remains within the organism (from Kattmann, 2015).

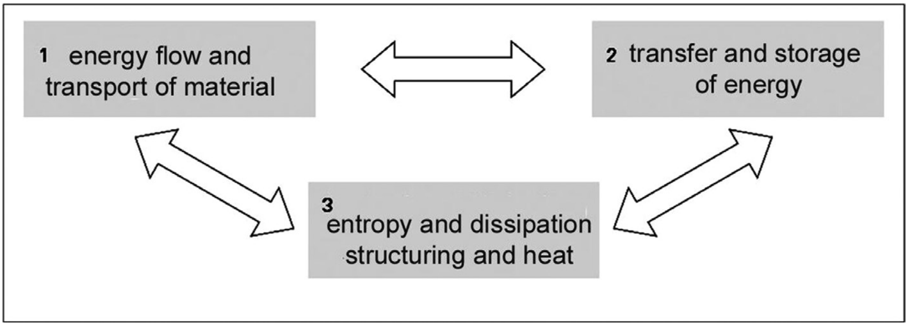

Figure 7 Concepts of energy in the context of biology

are described as the intake and output of energy in storage–flow models. Here, energy conservation is included as the equilibrating balance of flow (steady state). The reduced emphasis on the concept of energy conservation is also appropriate because in class the theorem of energy conservation can neither be proven nor demonstrated. One reason is that wasting heat cannot be avoided completely.

3 The relationship of entropy and the dissipation of energy is covered by structure formation and waste heat. Devaluation is reinterpreted as the disposal of entropy.

These three aspects are closely related to each other and complement each other (energy triplet). The terms entropy and energy should be connected to physiology and ecology, so that biological processes can be understood better. In this way, the terms contribute significantly to biological education.

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