BASIC ELEMENTS OF THERMODYNAMICS AND BIOENERGETICS

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In order to describe themodynamics and bioenergetics, we thought it could be useful to offer some basic concepts of these disciplines in an almost aphoristic fashion[1,2,3].

1. Thermodynamics is the branch of physics that describes the exchange of energy between systems and between these and the environment.
2. Thermodynamics studies the transformations of heat into mechanical work and viceversa.
3. In physics, energy implies the capacity or possibility in nature of performing work.
4. There is equivalence between mechanical work and heat.
5. All forms of energy in nature tend to transform into heat and heat tends to a uniform and random distribution.
6. There is potential energy and kinetic energy.
7. Thermodynamics studies the macroscopic properties of matter such as pressure, volume, temperature, mass, energy and entropy. These are intimately related to the statistically-governed microscopic arrangement of molecules.
8. Work can only occur when there is order in the distribution of the molecules in a system.
9. There is a gradient of potential energy, from order to chaos, that is capable of producing work.
10. Work always implies transformation, within a system, of order into chaos.
11. The first law of thermodynamics establishes that the amount of energy in the universe remains the same.
12. According to the first law of thermodynamics the different forms of energy can change from one to another.
13. Experience shows us that there are many phenomena in nature involving energy transformations that do not occur in spite of the fact that they do not violate the first law of thermodynamics.

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14. The transformation of caloric energy into other forms of energy and into work is theoretically possible according to the first law of thermodynamics; yet it is highly improbable it will occur spontaneously in nature.
15. The first law of thermodynamics does not mention the direction of the processes in nature.
16. The second law of thermodynamics constitutes an exception, a limitation, to the first law of thermodynamics.
17. The second law of thermodynamics establishes the direction of energy transformations.
18. Definitions of the second law of thermodynamics: "It is impossible for a self-acting machine, unaided by an external agency, to convey heat from one body to another at a higher temperature" (Clausius); "It is impossible to extract heat from a system and totally convert it into work, without causing some other change in the universe" (Lord Kelvin); "No process is possible whose sole result is the absorption of heat from a reservoir and its conversion to work" (Max Plank).
19. The second law of thermodynamics limits the type of energy transformations that can occur during physical or chemical processes. It predicts, statistically, in which direction is more probable that an energetic transformation will occur; establishes the possible reversibility of a reaction, and introduces the concept of entropy.
20. A simple way to express the second law of thermodynamics could be: "heat tends to flow from high to low temperatures. This is a statistical truism."
21. The concept of entropy is explained by the second law of thermodynamics.
22. In Greek *entropy* means transformation.
23. Entropy is that "transformation" which always accompanies the change of thermal energy into mechanical energy.
24.The entropy of a system is the measurement of its degree of disorder.
25. Entropy is the measurement of molecular disorder and is related to the concept of probability.
26. Entropy measures the loss of those characteristics that distinguishes a system from its surroundings. Less entropy means more differentiation of a system.
27. Experience shows that natural phenomena are unidirectional, thus they intend to increase entropy.
28. In irreversible processes entropy increases; in reversible processes entropy remains unchanged.
29. Entropy is also a variable whose change in value for two different moments of a system will tell us if a process may or may not occur.

30. The concepts of entropy, probability and randomness are inseparable.
31. Maximum entropy occurs at maximum thermodynamic equilibrium.
32. Maximum equilibrium of energy, or maximum entropy, occurs when energy reaches its maximum distribution and degradation.
33. When entropy increases, processes tend to become irreversible.
34. Entropy is the degree of disorder, the maximum equilibrium in which there can be no physical or chemical change and no work can be performed. Where pressure, temperature and concentration are uniform in all the system.
35. In a closed system (the universe), entropy (useless and random energy) tends to increase. In such a closed system processes can only be unidirectional and irreversible.
36. All systems have a finite amount of total energy. This total energy is stored as free energy and as "useless" energy of entropy.
37. Total energy, free energy and entropy are as important as volume, temperature, pressure and mass.
38. Free energy is useful energy.
39. The amount of free energy within a system is capable of "pushing" a physical or chemical reaction.
40. The amount of free energy always diminishes in any process that tends towards equilibrium.
41. When a system performs work, its internal energy (temperature) diminishes. The internal energy has been transformed into work.
42. When a system loses heat, it also diminishes its internal energy.
43. When a system reaches maximum entropy, free energy is at its minimum and is incapable of any further transformation.
44. The measurement of the changes in free energy within a system constitutes an indirect measurement of its changes in entropy.
45. There are two different kinds of internal free energy: one is Helmholtz free energy which tends to diminish at the expense of an increase in entropy, when a system changes from one state to another by means of variation in temperature at a constant volume. The other is Gibbs free energy in which the same occurs but under constant pressure.
46. Bioenergetic processes in living organisms are better understood by means of Gibbs free energy.
47. Hermann Nernst proposed a heat theorem that established that the entropy of all systems tends to zero as the absolute zero temperature is approached. At absolute zero temperature the entropy of a system would be zero. This is known as the third law of thermodynamics.
48. The transformation of the several forms of energy into heat is a simple and natural tendency that occurs with great caloric yield.

49. The transformation of heat into work requires complex systems such as man-made machines. They utilize the increase in volume produced by heating solids, liquids or gases.
50. Man-made machines use energy (heat) liberated from the oxidation (burning) of fuels to perform volume-pressure work through the expansion of a gas.
51. Chemical reactions occur in the direction of the most stable state. Theoretically they may also be reversible.
52. Reactions are exoergic (exothermic) when there is a decrease in free energy, and they are endoergic (endothermic) when there is an increase in free energy.
53. Chemical processes may be reversible only when free energy is added to them from an outside source.
54. Living organisms are biological open systems capable of easily exchanging energy with their environment. Thus they can incorporate free energy (nutrition) from their surroundings, and eliminate entropy or useless energy (heat) to their surroundings.
55. In biological systems phenomena occur under the strict limits of constant pressure, volume and temperature.
56. Biological systems transform chemical energy into mechanical energy under isothermal conditions. No man-made machine can do that.
57. In open systems processes may exceptionally seem reversible. Such is the case with living systems.
58. Living systems acquire certain degree of differentiation and information due to the free and useful energy they obtain from other systems (nutrition).
59. Biological systems use energy by burning metabolic fuels during the process of respiration.
60. Life is the capability of certain open systems (living organisms) to get rid of entropy and store a sufficient amount of free chemical energy capable of performing biological work.
61. It is more probable to be death than to be alive.
62. To inform means to give shape, to furnish structure. Through information the order of a system increases. Thus it is not surprising that the process of information has been identified with thermodynamics through entropy.
63. Claude E. Shannon applied the thermodynamic concept of entropy, as defined by Boltzmann in his statistical mechanics, to the theory of information.
64. The relationship between entropy as described by Shannon for information theory and entropy as described by Boltzmann for statistical mechanics is much more than a simple mathematical formality.

65. Information of systems is directly related to the orderliness of structures as a result of which type of information requires the degradation of free energy. One cannot get something for nothing.
66. Living organisms are highly improbable systems in disequilibrium whose integration and orderliness requires the expenditure of work and the existence of information stored in the genetic blueprints. The shift in the direction of less entropy is known as a negentropy shift.
67. Boltzmann established that the entropy of a system increases when its molecular structure acquires its most probable arrangement. The statistical definition of entropy has more validity when a large number of specimens of the system are considered.
68. Once a rock has fallen, the entropy of the system mountain-rock increases because it becomes a more probable system. Potential free energy is transformed into kinetic energy.
69. Equilibrium may be defined thermodynamically as a highly random state in which no net physical or chemical change occurs and there is no capacity for performing work.
70. If we regard entropy from the viewpoint of probability, we can say that the entropy of a system increases with the increase in equilibrium and disorder. During the downhill process towards equilibrium, the less entropic forms of energy, or those that have greater capacity to produce work, are being transformed into the most entropic forms.
71. Thermodynamics simplifies the understanding of complex physical phenomena because it deals with features of the physical world that are the gross properties of matter that are obvious to either one or all of our five senses and are measurable with a simple apparatus. Such properties are temperature, pressure, volume and composition. Even the concept of entropy, abstract as it may be, was deduced originally from these gross properties of matter.
72. Thermodynamics deals basically with the macroscopic properties of matter, it does not have to deal necessarily with the atomic composition of matter, that is to say with its microscopic properties. The microscopic behavior of systems became incorporated into thermodynamics through statistical mechanics at a later date.
73. Biological systems transform chemical energy directly into work in a much more efficient way than any heart machine engineered by human beings. This type of energy-work conversation is known as mechano-chemistry, and is the unique energy conversion utilized by all living systems to produce biological work, including mechanical work, from the chemical energy of food. No living creature works like a steam engine or like an electrical motor or a nuclear powered submarine.

74. All systems that produce mechanical work do so by degrading order, by consuming all the different types of potential energy that exist in nature, either gravitational, electromagnetic, nuclear or chemical. This is true for man-made machines or for those naturally existing machines such as living systems. The only difference is that living organisms produce mechanical work in a much more efficient way, by less destruction of the endowment of order existing in the universe and with less production of chaos in their surroundings.
75. Living cells exist as open systems that must conform to the laws of equilibrium or irreversible thermodynamics. They require a constant input of energy, ultimately derived from the radiant energy of the sun, and produce and utilize energy at a relatively fixed (isothermal) temperature. The heat of metabolism and contraction cannot be converted into work.
76. Living organisms are self-organizing systems. Machines cannot self-organize.
77. Living organisms can self-replicate. Machines cannot self-replicate.
78. Living organisms are self-repairing systems. Machines with information systems can occasionally self-repair.
79. Living organisms are non-equilibrium systems within their environment. Machines always tend to a thermodynamic equilibrium within the environment.
80. Living systems always have a stable internal temperature. They are isothermic while performing work. Machines increase their temperature when working.
81. Living systems are efficient in the use of energy. Machines are not efficient in the use of energy.
82. Living systems grow and increase in complexity as time goes by. Machines do not grow or increase in complexity.
83. Living systems use chemical energy to perform mechanical work. Machines use different types of energy, according to their design, to perform work.
84. Living systems liberate heat in their environment and machines produce much more heat than living systems. Which means that the production of entropy is higher in machines than in living systems.
85. Living systems built up information and it increases in relation with its surroundings. Machines never produce new information.
86. Living systems produce new information as they solve problems. Machines do not produce new information under the same circumstances.
87. Living systems know how to find and select nourishment. Machines, including computers, have to be fed with the fuels for which they were designed, that could be electricity, gas or carbon.

88. Living systems are complex and adaptative.
89. The information in living systems is in the DNA, thus they are self-organized.
90. Self-organized living systems have a permanent interaction within the entire cell's components and their environment.
91. Living organisms follow an open and closed cycle, accumulation and discharge, of gathering of free energy and the release of energy.
92. Living systems can store energy (ATP); information is also put in storage in the brain (historic information) and maybe stored in other parts of the organism.
93. That amount of free energy that is stored is always larger than the amount of energy spent on acquiring nourishment.
94. From a thermodynamic point of view, living systems use their own energy and information to survive as individuals.
95. Living systems use their own information stored it their DNA to survive as a species.

NOTES

1 Césarman, E., (1992), *Hombre y entropía*, México, Ediciones Gernika, 3a. ed.
2 Césarman, E., (1986), *Orden y caos*, México, Ediciones Gernika, 2a. ed.
3 Césarman, E., (1996), *Thermodynamics of the Heart. Collected Papers 1977-1996*, México, Robles Hermanos.