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Thermodynamics and biology (Inaugural Address)

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It is my privilege and pleasure to be here this morning to participate in the opening session of this prestigious *International Conference on Chemical and Biological Thermodynamics*. I thank the International Organizing Committee for giving me the honour to inaugurate the Conference.

As a mechanical engineer, I have always admired the way thermodynamics grew from the study of heat engines which were invented in the 19th century for converting heat energy into mechanical power and ushering the industrial revolution. The initial development of this field was very rapid. By 1900, the subject was firmly established and although its application was originally restricted to thermal engineering, its laws were soon recognised to be of such great generality as to be useful and important in many other branches of science .

One of the beauties of thermodynamics is its remarkable intellectual structure and philosophy. It deals with the mathematical relations between observable properties and is independent of the microscopic nature of matter. This has indeed great advantages. For example, when the classical mechanics had to be abandoned in favour of quantum mechanics of atoms and molecules, the laws of thermodynamics remained unchanged. In the engineering context thermodydnamics deals with the macrostructure of matter and does not concern itself with the events happening at the molecular level. The laws and concepts of thermodynamics are thus independent of either the present or the future theories on the ultimate nature of matter.

My excursions in the field of thermodynamics have been as a mechanical engineer. I find thermodynamics to be intriguing and inspite of that or more so on account of that, very fascinating. The philosophical contents of thermodynamics add charm to the subject. Teaching thermodynamics to engineering students has given me an impression that the subject is confusing to them. I have often wondered why engineering students find thermodynamics confusing. Obert in his book "Concepts of Thermodynamics" says that thermodynamics was developed by Physicists. Their immediate early objective was the equation: $TdS = dU - PdV$. We may take Obert seriously or otherwise, considering that Obert dedicated his book (pet name- "Concepts"), to "the perplexed student who enquires: What are the independent variables?" Obert was my teacher at the University of Wisconsin back in early 1960's. With reference to Tds equation, he argued that the physicist and the chemist emphasised that differential function for heat and work were inexact, i.e., heat and work could not be expressed as functions of 'U' and 'V'. Students of physics are not so concerned with energy balances and the aforesaid explanation is considered sufficient by them.

Engineering students are more concerned with energy equation than with Tds equation and to speak of inexact differentials for an energy equation is pointless, as well as confusing. Q.E.D.

Confusion does not arise for closed system if we declare that all variables are functions of the single variable of time. The engineering open system, however, introduces, a new complexity. In the open system heat and work are variables pertinent to a region and we cannot speak of inexact differentials. In such systems, in general, the independent variables are time and position, some times both independent variables are required and at other times only one. The quantity Q, for example, is used both in closed and open systems; in the former it is a time increment and in the latter it may be a position increment. To compound the confusion, it is a common practice in thermodynamics to speak of "path functions" and to refer to differentials as infinitely small quantities.

The pre-requisite of the First Law of Thermodynamics is contained in the axiom: The internal energy of a system is a property. On this axiom was built the First Law which is the law of conservation of energy. If relativity effects are considered, the statement is to be modified to declare that the First Law is the law of conservation of mass and energy. At the time of its discovery, in the middle of the nineteenth century, the First Law was an outstanding discovery because at that time, the real nature of heat energy was not yet clearly established. But once the kinetic hypothesis of heat had found general acceptance, the First Law became an easily understood consequence of the basic law of mechanics.

The Second Law on the other hand, cannot be derived from purely mechanical laws. It relates to the statistical nature of heat. Its self-consistent formulation is possible only for ensembles of systems that are to in statistical equilibrium. The formulation of the Second Law from the foundations of statistical mechanics asserts the existence of a state variable, the entropy. The customary formulation of the Second Law goes far beyond the assertion of the existence of the entropy, stipulatig that any thermodynamic process in a thermally isolated system will result in increase of entropy of the system.

In thermal physics, chemistry, biology and in many other areas, one has to deal with collection of quantities, they may be molecules or even a sequence of data. Often properties of aggregates, rather than the individual elements, may be of interest. It is also possible that though information may not be available about the elements, yet we could deal with the collection. Statistical mechanics represents such a case where we are unable to say much about individual molecules, but are able to make prediction about properties such as pressure, temperature and density for a collection of molecules.

In addition to probability and statistics, methods of handling aggregates are provided by information theory. For example, the analytical form of entropy function in statistical mechanics and the way we derive the distribution functions of statistical mechanics, suggest a relationship between entropy and information and an ensemble approach is used to provide link between the two concepts. In an ensemble of many members, the eigenstate of each member can be regarded as a symbol and the sequence of eigenstates constitutes a message which is interpreted by the information theory.

The thermodynamics of biological processes taking place on the surface of the earth is remarkable. These processes are powered by energy coming from the sun or stored energy from past solar radiation.

The entropy function has been an enigma to students of thermodynamics. Orgiallly postulated as a function of state, it was soon discovered to provide the most general and succinct statement of the condition of equilibrium in any system. With the rise of kinetic theory, entropy provided the most universal notion of mechanical irreversibility. Statistical mechanics used entropy to bridge the gap between statistical formalism and phenomenological thermodynamics. The modern information theory relates entropy to information and ultimately to observer. These considerations make entropy central to biology and provide answers to many conceptual difficulties.

There are few ideas in science which have been as difficult to comprehend as the second law of thermodynamics and accompanying concept of the entropy function. These concepts have engineering origin and were first introduced by Sadi Carnot. Carnot's 1824 monograph was entitled "Reflections on the Motive Power of Fire ad on Machines Fitted to Develop that Power". From this origin in steam engines, several concepts have arisen which have profoundly influenced physics, chemistry, biology and a number of related sciences. The relationships between entropy, work and information and the informational character of biology stress the strong symbiosis between biology and thermal physics.

Thermal energy, diffusion and Brownian motion are three related topics of thermal physics which are of great significance in understanding much of biology in terms of its physical foundations. Temperature at molecular level means the moving, twisting, turning, oscillating and general jumping around of molecules. The elegant atomic models give a false static view of molecules. In drawing structures and buildings models, we tend to loose sight of the persistent random motion which is a necessary part of the description of matter. This thermal energy is responsible for the decay of ordered system to a stage of maximum disorder or maximum entropy, chemical reaction, diffusion and Brownian motion.

In classical thermodynamics, we use notions of equilibrium with characteristics such as time-invariance and spatial inhomogeneity. No biological system is at equilibrium, so the traditional theory can only be used to obtain limited statements and not detailed predictions. Parts of a living organism may be close to equilibrium with respect to some processes while far from it with respect to others. The useful domain of thermodynamics has been extended by the development of nonequilibrium theory and the thermodynamics of steady states which allow further insights into near-to-equilibrium system by such concepts as local variables, entropy flow and entropy generation.

To handle chemical and biological systems, a transition in thinking from the gross macroscopic behaviour of matter to a consideration of submicroscopic details is involved and a number of conceptual tools are required. They include probability and statistics, information theory and statistical mechanics.

The organisms which carry out photosynthesis are primary products or the first trophic level. The organisms which live on the primary producers, the herbivores, are the second trophic level and the carnivores that feed on the herbivores are the third trophic level. This food chain is a simplification whereas the ecoreality comprises food webs rather than chains.

Organisms at the first trophic level use a fraction of their primary productivity for their physiological functions and the rest goes to storage. Biology is dependent on the earth taking in sunlight and radiating infrared energy to outer space. The ultimate source of all our energy and negative entropy is the radiation of the sun. A photon interacting with a material particle on earth lifts one electron from an electron pair to a higher level. This excited state has a short life time and the electron drops back within 10-100 nanoseconds to the ground state giving off its excess energy. Life has learnt to catch the electron in its excited state, uncouple it from its partner and let it drop to the ground state through its biological machinery utilizing its excess energy for life processes.

The sun will not be a source of "negentropy" without a sink for flow of thermal energy. The earth surface does not gain net energy from the sun but remains at an approximately constant total energy reradiating as much energy as is taken up. It is not the energy per se that sustains the life but the flows of energy through the system. The concept of flow of energy gives us a powerful basis for physical analysis of a system and its exploitation in physics continue to reveal exciting results which are of immense interest to many fields of science, particularly ecology.

Scientists are able to deal with the concept of free energy formation of living material relative to some standard state of starting material. The concept applies to problems of cell-division, predator-prey relations and trophic ecology. The insights of thermodynamics combine with those of chemistry, biochemistry and trophic ecology to explain the relationship between energy flows and biological processes.

Thermodynamics has various levels of abstraction but the fact is that its formal structure ultimately rests on many an empirical generalization. At each stage it is necessary to relate the constructs to laboratory experiments. The empirical parameters of thermodynamics fall into two broad categories: those derivable from mechanics and analytical chemistry and those which are exclusively thermodynamics. Among the former are quantities like volume, pressure, mass, density, surface tension, mole number, gravitational potential, etc. The pure thermodynamic quantities relate to the measurement of temperature. Energy is a mixed case.

Traditional thermodynamics gives insight into various stable systems. But is does not say much about the process by which a system moves from one state to another. Such problems are dealt with by mechanics, hydrodynamics, chemical kinetics and electrodynamics. Thermal aspects remain in all these treatments due to friction, viscosity, and explicit temperature effects. No branch of molecular physics escapes an involvement with thermal factors and efforts are made to extend various disciplines into a more generalized thermodynamics. Much has been done for the understanding of the generalized basis of chemical cycles in nonequilibrium system such as those encountered, for example, in ecology. Let me conclude by saying that the fascinations of thermodynames are endless.

It has been my pleasure to be here this morning among the distinguished scientists in this prestigious IUPAC conference. I once again thank the organizers for their kind invitation to me to inaugurate this conference. It is with great pleasure that I do so. I am sure you would enjoy your stay in this beautiful holy city of Amritsar and that scientific deliberations of this conference would be most rewarding.