3rd INTERNATIONAL WORKSHOP
ADVANCES IN CLEANER PRODUCTION

''CLEANER PRODUCTION INITIATIVES AND CHALLENGES FOR A SUSTAINABLE WORLD''

From Modern Thermodynamics to How Nature Works – a View of Emergent Paradigms Associated with Sustainability

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Abstract

The importance of the second law of thermodynamics, already called the most metaphysical of all laws of nature, as key to understand the questions of ecology and sustainability is discussed, as well as the a fast paced conceptual evolution that gained momentum in the last 50 years , changing our view of Nature. Classical thermodynamics, is associated with the tendency to disorganization, while nonlinear irreversible thermodynamics, introduces the concept of emerging ordered dissipative structures, a necessary tool to deal with the nature of living beings and its social, economic and ecological aggregates. Most introductory texts in thermodynamics are limited in scope , restricting the expositions to the study of equilibrium systems- meaning the study of idealized, infinitely slow process, hardly a situation encountered by the professional life, and far away from how nature works, as an coherent and complex aggregate of dissipative processes. Dissipative structures are living (i.e. amoeba and humans), and non-living (i.e. tornadoes, hurricanes, the gulfstream), or composed by non-living and living, like economies, factories, social structures. The author's teaching experience gives evidence that undergraduate students are ill prepared for the discovery and fascination of how nature works, and consequently striving for sustainability. Systems of major interest to the issue of sustainability are open, coherent, purposive, and irreversible. Irreversible thermodynamics is presented as an element for the understanding and unification of a wide range of disciplines needed by the student, but still subjected to a fragmentation of a somewhat bureaucratic nature. This integration benefited from the enormous development of computers, and its use in the study, as an example, of nonlinear dynamics system with wide applications in various fields including engineering, biology, ecology, economics, and sociology..

Keywords: *Thermodynamics, open systems, non-linear dynamics, sustainability.*

1 Introduction

"It makes me so happy. To be at the beginning again, knowing almost nothing…The ordinary-sized stuff which is our lives, the things people write poetry about-clouds-daddfodils-waterfalls …these things are full of mystery, as mysterious to us as the heavens were to the Greeks…It's the best possible time to be alive, when almost everything you thought you knew is wrong" Tom Stoppard, cited in "Complexity a Guided Tour" (Mitchell, 2009)

"I want to know how God created this world. I am not interested in this and that phenomenon, in the spectrum of this or that element. I want to know His thoughts: the rest are details" Albert Einstein

No physical law is as important as the second law of thermodynamics, already called the most metaphysical of all laws of nature, as an instrument to fulfill Einstein's main interest. In the last 50 years a fast paced conceptual evolution gained momentum and "…changed our view of Nature" (Kondepudi and Prigogine, 1998). Considering classical thermodynamics as an initial point, associated with the tendency to disorganization, this conceptual evolution reached to nonlinear thermodynamics, introducing the concept of emerging ordered dissipative structures, which are part of the nature of living beings and its social, economic and ecological aggregates. Hierarchically, linear irreversible thermodynamics could be placed between classical and nonlinear thermodynamics. Linear irreversible thermodynamics is, as pointed out by Katchalsky (1974), a *coordinated theory of irreversible thermodynamics*, developed based "on the fundamental work of Onsager", consisting in a "new branch of thermodynamics." Within this theory the inequalities of classical thermodynamics (second law) are replaced with equalities, resulting in "thermodynamically-fundamented" transport equations. As pointed out by Prigogine (1967), *linear nonequilibrium thermodynamics* is today a classical subject, limited however to the vicinity of equilibrium. In the far-from-equilibrium region n*onlinear thermodynamics* introduces the concept of dissipative structures associated with the emergence of order in both time and space. Dissipative structures are living structures, (i.e. amoeba and humans), and non-living (i.e. tornadoes, hurricanes, the gulfstream), or composed by non-living and living, like economies, factories, social structures, and ecological structures.

As recently pointed out by Kondepudi and Prigogine (1998) , most introductory texts in thermodynamics (to engineers , as an example) are limited in scope , restricting the expositions to the study of equilibrium systems- meaning the study of idealized, infinitely slow process, hardly a situation encountered by the engineer in his professional life, and far away from how nature works, as an coherent and complex aggregate of dissipative processes. In relatively simple transport systems, not too far from equilibrium, the subject of irreversible linear thermodynamics is an effective tool to deal with transport processes, even in living systems (Katchalsky, 1974). In near equilibrium transport processes, flows are linear functions of the so called "thermodynamic forces ", and can be treated with the use of thermodynamics methods, independently of specific kinetic models. As pointed out by Nicolis and Prigogine (1977), with the appearance of Onsager's reciprocity relations, thermodynamic methods was capable to "provide useful information" in transport phenomena.

Bénard instability, (Bénard, 2010), is a classical evidence that Boltzmann's "order principle", is inapplicable to dissipative structures (Nicolis and Prigogine, 1977). Those structures are associated with conditions that results in the amplification of fluctuations, instead of damping. The author's teaching experience gives evidence that undergraduate students are ill prepared to the discovery and fascination of how nature works "The multiplicity of solutions in nonlinear systems corresponds to a gradual acquisition of autonomy from the environment" (Nicolis and Prigogine, 1977) – nonlinearity is a necessary condition for the existence of life: the study of nonlinear dynamic systems deserve more attention that has been given, and concepts associated with it, like sensitivity to initial conditions, bifurcation, attractors, deterministic chaos, need to be presented to undergraduate students. This mathematical needs can be satisfied, avoiding at the same time limiting the search for truth to the tedious pen and paper mathematics, and instead, incorporating the intense use of visualization, and e-learning resources, based on computer techniques. The richness of materials available in the internet, including imaginative applets; tutorials; abundant visualization; consists in an efficient, if not unique tool to introduce certain complex subjects. The internet site CalResCo (2010) has several links to subjects like *complexity*, *automata*, *attractors*, *chaos*, *fractals*, *non-linear dynamics*, *self-organization* where highly effective teaching material can be found. In introductory disciplines destined to deal with this highly complex field, intense use of e-resources is either extremely useful, if not absolutely necessary.

Living beings reproduce with invariance – they are "self-reproducing machines", (Monod, 1971)),that build themselves from bottom up, living and surviving far from equilibrium, and exhibiting properties typical of Monod's "*strange objects*" (a leaf, a flower, a tree) Monod originally defined strange objects as ¨products of human art or workmanship" (a pen, a car, a plane) , distinct from *natural objects* (a cloud, a rock, a mountain). The fascinating evolution in the last 50 years, has led to the study of ecological system as a complex and integrated whole This view is clearly expressed in the title of the work of James Kay (2000), " Ecosystems as Self-Organizing Holarchic Opens Systems: Narratives and the Second Law of Thermodynamics " . Kay coined the term "SOHO" to describe those systems .The author also ended up with four letters to describe those systems: "OCPI" (presently changed to PICO) - meaning systems which are Open, Coherent, Purposive, and Irreversible, in a paper presented at ICHEAP4 (Bittencourt, 1999).

We stress here that the utilization of methods of experimental mathematics; intense use of visualization, applets, tutorials, are very valuable tools to the comprehension of discrete dynamical system (i.e. population dynamics); visualization of fractals; cellular automata; oscillating reactions, to mention a few examples. The resources necessary to teach this complex subject, requires a fascinating machine - the computer. Only a machine can find certain truths and the system's behavior, those that cannot be reached from a consistent set of axioms-an example is the nonlinear dynamic systems sensitivity to initial conditions, found by accident by Lorenz. In the presentation derived from this paper it will be presented a set of e-resources collected while teaching on the body of knowledge, the systems, which Kay (2000) called "SOHO", and the author called "OCPI",(presently PICO).

According to (Borwein and Bailey, 2004) in "Mathematics by Experiment-Plausible Reasoning in the 21st Century", mathematics may yet to become an empirical discipline, a place "where things are discovered because they are seen. It is proposed to induce the enthusiasm of future and practicing engineers and scientists, into a solid perspective of SOHO systems- that is, understanding how nature works, trying to reach this goal as early as possible, in introductory courses -ultimate motivation of Kondepudi and Prigogine (1998), when they wrote "Modern Thermodynamics".

2 Discussion

The linear region

The linear, irreversible region treats the question of entropy production in irreversible processes by specific forces associated with specific fluxes , i.e. , with the fluxes of energy, volume, and matter transported , respectively by the "forces" Δ(1/T), Δ(P/T) , and Δ(-μ/T) , where P is the pressure, T the absolute temperature ,and μ the chemical potential (Katchalsky, 1974). Phenomenological Equations allow the simultaneous coupling of all forces with all fluxes. Well known examples of this interference, is thermo-electricity, the Soret effect, and Knudsen flow. Observed coupling effects phenomena demanded the utilization of the Phenomenological Equations. Referring to reverse osmosis: "The introduction of the cross coefficients is not arbitrary but is required by the very nature of the phenomena taking place in the membrane" (Katchalsky, 1974). Katchalsky "explains" irreversibility as a property of systems that develop any gradient as a first derivative of time , therefore not invariant with respect to the transformation t to –t, a while equations like the wave equation , which are second derivative of time are invariant. The author utilized the formalism of linear irreversible thermodynamics in his PhD thesis (Bittencourt, 1975)

The nonlinear region

The study of the dynamics of the nonlinear irreversible region, establishes conditions for the appearance and typical behavior of nonliving dissipative structures in systems that are kept far from equilibrium, which in the macroscopic point of view (Nicolis and Prigogine, 1977), are distinct from equilibrium processes. A particularly distinct category of dissipative structures are living beings: self organized, built from within, consisting in SOHO systems as coined by Kay (2000). As pointed out by Kauffman (1994) systems that are "…around us, sustain us , are created by us, grafts the energy from the sun into the great web of biochemical, biological, geologic, economic, and political exchanges that envelops the world". How this complex system aggregates into a even higher complex system, it is still an "unexplored frontier", in the words of Heinz Pagels as quoted by Melanie Mitchell (Mitchell 2009). Its remains to be understood, exactly how half a million ants nearly blind and "minimally intelligent ants start a march in the Amazon forest , devours all prey in its path, in the end building with their bodies a nighttime shelter in the form of a ball around their larvae and mother queen". As mentioned by Mitchell (2009), what emerges from the whole, the "superorganism", is "collective intelligence". Stuart Kauffman (1995) adds that "Biologists, subliminally aware of such spontaneous order, have nevertheless ignored it and focused almost entirely on selection". Those living dissipative structured individuals exist as self reproducing machines, endowed with the capacity of reproduction with invariance- Monod (1971) defines as *strange objects* the products of human art or workmanship (i.e. a knife, a pen, a car). However, Monod (1971) classifies living creatures (i.e. bees, ants, butterflies), also as *strange objects*, as dissipative machines incorporating four attributes: *teleonomy*, *autonomous morphogenesis*, *and reproductive invariance*. Georgescu Roegen (1976) in a seminal book, writing about the entropy law and the economic process, argues against the mechanical analogue interpretation of the economic process, traditionally seen as "…a circular flow production and consumption with no outlets and no inlets, as elementary textbooks depict it". Georgescu adds," "Not even wars for the control the same nations fought for the control of the world's natural resources awoke economists from their slumber".

Prigogine, Kauffman, Coveney, Gödel, and Mathematics by Experiment

"Modern Thermodynamics", (Kondepudi and Prigogine, 1998) was written as an introductory text destined to correct an educational gap in the teaching of thermodynamics. Engineers deal with irreversible dynamic systems, developing, building, managing production units, which suck low entropy from the biosphere, discharging high entropy. The evolution in the last 50 years established the need to incorporate a wide range of relatively new language, new terms, concepts, knowledge, some hardly or never mentioned in undergraduate teaching, and, most importantly, reaching from the hard sciences to humanities – the work of Prigogine builds this bridge. Kauffman says, extending the reach of the aggregate of those theories, "Democracy may be far and away the best process to solve the complex problems of a complex evolving society, to find the peaks on the coevolutionary landscape where, on average, all have a chance to prosper". Peter Coveney and Roger Highfield (1995)", mention Gödel theorem, stating that "…the logistic doctrine, according to which all mathematics may be deduced from the axioms of logic, was demonstrated to be incorrect". And quoting John Barrow (on page 28), say Coveney and Highfield (1995): "If we define a religion to be a system of thought which contains unprovable statements, so it contains an element of faith, Gödel has taught us not only is mathematics a religion able to prove itself to be one." Therefore, there are truths that can only be found by experiment. Commenting on Lorenz discovery of the sensitivity to initial conditions of nonlinear dynamic systems, "Lorenz error revealed the dependence on initial condition of a set of dynamic nonlinear equations by accident widely known, as reported in detail by Grace Conyers (2009). According to Borwein and Bailey (2004), "…the utilization of advanced computing technology in mathematical research – is often called experimental mathematics". The mathematician will perform experiments like in a laboratory, as chemists and physicists do. Experimental mathematics uses computation for: gaining insight and intuition; discovering new patterns and relationships; using graphical displays to suggest underlying mathematical principles; testing conjectures; exploring a possible result to see is if worth formal proof; suggesting approaches to formal proof; replacing lengthy derivations with computer-based derivations; confirming analytically derived results (Borwein and Bailey 2004, p 2-3 ***)***.

3 Conclusions

In a previous work Bittencourt (1999) pointed out that the second law, is generally introduced following traditional methods, with a *dependence* (Denbigh 1971), on the use of *heat engines*, if based on Clausius or if based in Poincaré approach, in *the existence of perfect* gases According to Margeneau and Murphy (1943), writing about the second law, "In most textbooks of thermodynamics the order of presentation parallels the *historical development* of the subject", adding that as a result, "the critical student may feel the need of a more logical and formal approach." It is necessary the incorporation of nonequilibrium thermodynamics in introductory texts, including systems far from equilibrium, the nonlinear region, associated with emergence of order; complexity, and purposiveness, as qualities in biology, sociology, and economy. As pointed out by Robert M. May (1976), "linear systems...tend to dominate even moderately advanced University courses in mathematics and … ill equips the students to confront the bizarre behavior exhibited by the simplest of discrete nonlinear systems". An internet based text created by Professor S. Bhattacharjee (Bhattacharjee, viewed February 2011); has been used by the author since 2005, due to its well balanced structure and effective use of visualization. Applets and tutorials, e-learning sites, have been used by the author to illustrate and teach concepts like; fractals; bifurcation and attractors chaos theory; sensitivity to initial conditions in nonlinear dynamics; cellular automata; bifurcation diagrams; predator –prey Lotka–Volterra equations ; active transport mechanisms , to mention just a few items. The scientific evolution in those last 50 or 60 years poses a formidable challenge to the scientist and technical man. Ecological challenges demand prompt action. Experimental mathematics is now firmly established as a laboratory tool for mathematics. Immanuel Wallerstein (1997), points out to "… the fundamental challenge from within the community of natural scientists themselves, from the now very large group who pursue what they call "complexity studies". Recently, (Per Bak, 1996) considered the question of self-organized criticality: a "new way of viewing nature", as subject to catastrophic events. Also, inequality seems to be more impacting and damaging to the quality of life, from education, criminality, to life expectancy, than poverty itself (Wilkinson and Picket, 2010). We are challenged to dedicate ourselves to the betterment of mankind-to build an appropriate education to contribute to this end, incorporating the scientific revolution of the last 50 years.

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