Dissipative structures in nature and human systems

E. B. P. Tiezzi[1], R. M. Pulselli[2], N. Marchettini[2] & E. Tiezzi[2]
[1]*Department of Mathematics and Informatics, University of Siena, Italy*
[2]*Department of Chemical and Biosystems Sciences, University of Siena, Italy*

Abstract

Evolutionary physics studies the general behaviour of non equilibrium systems, subject to non-linear rules. Through the observation of these systems, physical chemistry begins to understand phenomena that have complex and self-organising behaviour. In practice, in order to understand life and its ability to self-organise, evolutionary physical chemistry studies phenomena which present novelties, i.e., in which order is horn from chaos (*order out of chaos* is an expression dear to the school of Ilya Prigogine, father of evolutionary physics and winner of the Nobel Prize in Chemistry in 1977). This paper presents a discussion on self-organization processes in dissipative structures, in order to highlight the general conditions for raising complexity and generating order in nature. In particular, variation of entropy and thermodynamic information in self-organizing systems were briefly introduced. Examples of dissipative structures in nature were presented, such as oscillatory reactions, hurricanes, and also human society. This would inform next generation designers.

Keywords: dissipative structures, entropy, information, non equilibrium thermodynamics, Bènard Cells, hurricanes, cities.

1 Introduction

A Dissipative Structure is a thermodynamically open system operating far from thermodynamic equilibrium, that exchanges energy, matter, and information with the external environment. In this kind of systems, organization can emerge through a spontaneous self-organization process, by virtue of the exchanges with the external environment, that generates a formation of both spatial and temporal

www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/DN080301

ordered structures, in which interacting constituents show long-range correlations.

Example of self-organization process in dissipative structures are the oscillatory chemical reactions. In the fifties and sixties, two Russian scientists, Boris Belousov and Anatal Zhabotinsky, discovered the most famous of all oscillatory chemical reactions and described it in detail (it is now known as the Belousov-Zhabotinsky reaction or simply the BZ reaction). The discovery sparked an intense debate in the field of applied physical chemistry. Oscillatory reactions are events in which complex reactions produce spontaneous variations in certain chemicals present in a solution. Under suitable test conditions, this phenomenon creates spectacular and rapid changes in colour. In particular. the periodic variations of the concentration of the reaction intermediators and catalysts corresponds to a progressive variation of their geometry, form and colour.

The creation of spatiotemporal structures is extremely interesting because it causes macroscopic self-organisation that depends on microscopic interaction between organic and inorganic elements in the system. Order is created from an initial state of uniformity and chaos. Interaction between the elements is induced by kinetics and internal diffusion; it is required to create structures organised in space and time. Oscillations can only be observed in systems in which there is a constant exchange of energy and matter with the exterior, systems that are far from equilibrium, i.e., in a dynamic, variable and non homogeneous state.

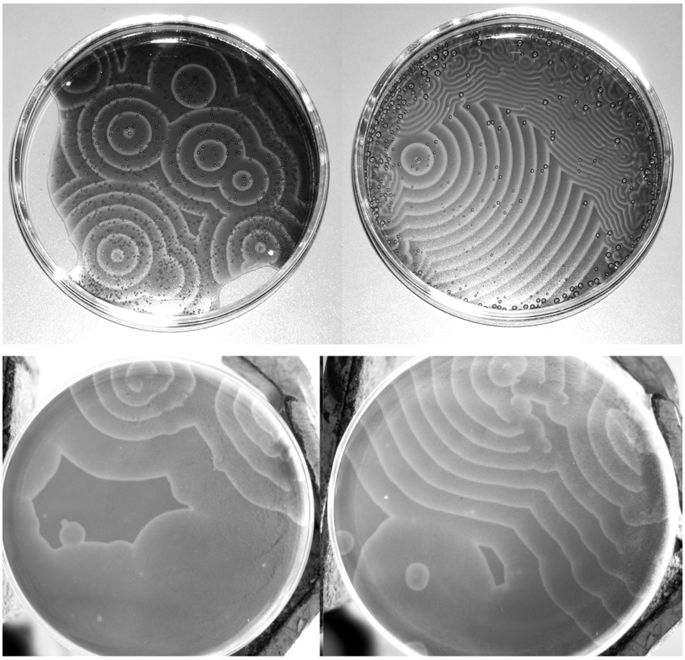

Figure 1: An example of Belousov-Zhabotinsky reaction.

According to Prigogine, in the condition of non-equilibrium, which seems to be the absence of physical order, fluctuations of energy can produce *order out of chaos*. The arising of space configurations and time rhythms in dissipative structures is a phenomenon known as 'order by fluctuations'. Prigogine and Stengers [1] said: "we can imagine dissipative structures as *giant fluctuations* maintained by flows of energy and matter". Therefore, dissipative structures are the result of fluctuations maintained in a steady state; once established, steady states can be maintained with respect to a huge class of perturbations.

2 Variation of entropy and thermodynamic information in dissipative structures

Jeffrey Wicken [2–4] studied processes of increasing complexity and self-organization in terms of thermodynamic information. He observed that the formation of dissipative structures, such as living systems, and their evolution are due to processes of energy and matter randomization, with 'randomization' meaning a random distribution, allocation or delivery of energy and matter inflows that allows complexity increase within a system.

According to Wicken, the macroscopic thermodynamic information I_M of a specific state is given by the addition of two terms:

$$I_M = I_w + I_e \tag{1}$$

where $I_w = -k\ln w_i = -S$ is the negentropic component of the chemical information depending on the decreasing number of microstates and $I_e = (E_i - \underline{A})/T$ represents the energetic component. The latter relates to the entropy output from the system due to energy dissipation.

In particular, negentropy I_w is given by:

$$I_w = I_{th} + I_c \tag{2}$$

Where I_{th} is the thermal information and I_c is the configurational information. The former refers to the distribution of the state's thermal energy, and the latter to the number of microstates in any possible configuration. In other words, these components are concerned with the reciprocal structuring and energetic relations among the elements in the macrostate (intra-molecules information) due to the increased differentiation of microstates and their inter-molecules information.

According to the principle of the second law of thermodynamics, the variation of information, including a system and the environment, must be negative, while entropy increases:

$$\Delta I_c + \Delta I_{th} + \Delta I_e < 0 \tag{3}$$

This represents the thermodynamic limits to chemical information transfer between two different states. Considering an energy flow from a hot source to a cold sink, entropy always increases ($dS_s > 0$). As asserted by Harold Morowitz [5], the entropy of an intermediate system, behaving like a dissipative structure, may decrease ($dS_i < 0$) if there is an energy flow, with the only restriction being that:

$$-dS_i \leq dS_s \tag{4}$$

In this case, the negative variation of entropy in the system corresponds to a positive variation of information given by the components ΔI_{th} and ΔI_c. In terms of information, inequality (4) is equivalent to:

$$\Delta I_{th} + \Delta I_c < - \Delta I_e \quad (5)$$

where the term ($\Delta I_{th} + \Delta I_c$) represents the information within the (intermediate) system and the term ($- \Delta I_e$) corresponds to the disorder generated by the entropy dissipation to the external environment.

We may apply this reasoning to the biosphere, which is a closed thermodynamic system: the continuous radiant energy inflow from an external source (the sun) demands an energy randomization, before part of the low quality energy leaves the planet. Over millions of years, this has led to the emergence of new organized structures and to a higher diversification (life, evolution, bio-diversity), corresponding to an increase of information. The processes by which complex chemical and biological structures emerge with time from simpler structures was named *Anamorphosis* by Wicken.

3 Dissipative structures in nature and human systems: some examples

In complex systems, organization usually emerges spontaneously. According to the law of *least resistance* [6], constitutive elements within a self-organizing system modify their interactions with other elements, looking for the most advantageous. Interactions between system constituents, that are neither isolated nor free, involve continuous reciprocal adaptation; each individual acts and reacts according to actions and reactions of the other individuals. This process, generated by competition and cooperation among the components, each pursuing its own aims, does not stop until organization that guarantees harmonious, non conflicting interactions among individuals is achieved.

The main condition to maintain a state far from thermodynamic equilibrium, according to the concept of dissipative structures, is that the system must not be isolated and must exchange energy and matter with the external environment. This situation highlights the importance of interactions with the external environment; these also involve the constituents of the system for self-organization. Nicolis and Prigogine [7] provide some examples. A cubic centimetre of water at ambient temperature is characterised by the disordered thermal motion of its molecules; if it is subject to a winter storm, it self-organizes in the peculiar dendritic structure of a snowflake.

There many examples in which groups of agents, pursuing their own consistency, transcend themselves and acquire collective properties.

The Scientific Visualization Studio (Goddard Space Flight Center della NASA), visualized the trajectory of Hurricane Katrina, in August 2005, analyzing data of sea surface temperature and clouds formation. This visualization shows the cold water trail left by Hurricane Katrina from August 23 through 30, 2005. They highlighted that "hurricane winds are sustained by the heat energy of the ocean, so the ocean is cooled as the hurricane passes and the energy is extracted to power the winds".

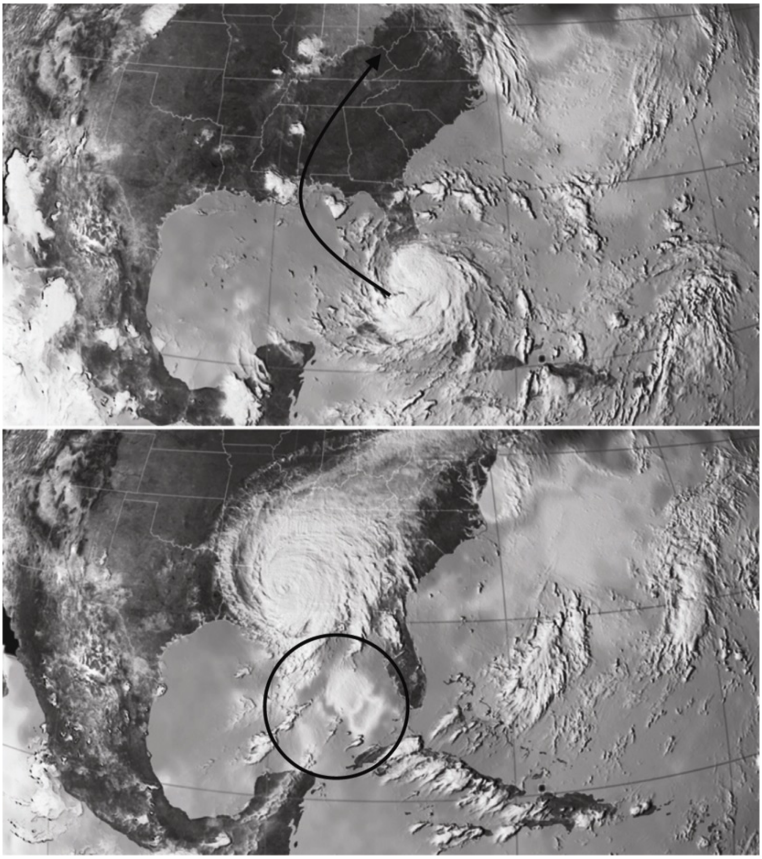

Figure 2: Cold water trail left by Hurricane Katrina. Elaboration of data of Sea surface temperatures and satellite images from August 23 through 30, 2005. The sea surface temperatures are 3-day moving averages based on the AMSR-E instrument on the Aqua Satellite, while the cloud images were taken by the Imager on the GOES-12 Satellite (available at: http://svs.gsfc.nasa.gov/goto?3222).

Hurricanes behave like dissipative structures. Thought and life also belong to the category of complex living systems.

Societies, too, result from the aggregation of groups of individuals, and show emerging collective properties that single elements do not have [8]. For example, we know that certain individual behaviour is induced by society and how difficult it is to change a social behavioural trend or an economy, despite widespread awareness of the need to do so [9].

The configuration of a complex system, or organization of parts into a whole, depends on interactions among constituents of the system (responsible for the entropy change d_iS) and perturbations from the external environment (responsible for the entropy change d_eS) [10]. The configuration is always dynamic: it is not static in time but changes whenever external conditions change.

The ability to self-organize into complex structures and to self-maintain in space and time is aimed at conserving a steady state (dynamicity, diversity, life), far from thermodynamic equilibrium and with low entropy, by virtue of interactions among constituents and other systems.

How can a society or a city be conceived as a dissipative structure?

Absorption of external input (negentropy) and emission of internal output (entropy, heat) is a principle that works for social systems, economics, human settlements and all their dynamics. Cities absorb flows of high quality energy from the external environment and emit heat, wastes and pollutants; their internal entropy decreases by self-organization in the form of structures, information, social patterns and economy. Resource flows feed these dissipative cities, as if they were ecosystems composed of organisms and are metabolized and continuously used to sustain its ordered structure during the time.

Cities are physical systems in contact with various sources and sinks; matter and energy flow through them from the sources to the sinks.

4 Conclusions

Evolutionary thermodynamics and complex system theory provide a potential scientific background for understanding the general behaviour of living systems. They provide an opportunity for understanding nature, cities, society and life. Knowledge of nature must come from a global, systemic view of events and from study of interactions between different elements in the various forms of matter, energy and information in time and space [11]. The perception of complexity and dissipation in far from equilibrium systems gives a theoretical framework that also works for reloading principles of aesthetics.

The challenge and novelty of contemporary design would probably be in considering the dynamics of natural systems, flows of energy and matter, information exchange and the spontaneous formation of ordered structures. The task of the next generation of designers, aware of the complexity of the dissipative systems far from thermodynamic equilibrium, is to think coherent shapes within a dynamic world.

References

[1] Prigogine, I., Stengers, I., *The new alliance*. Gallimard, Paris, 1979.
[2] Wicken, J. S., Information transformation in molecular evolution. *Journal of Theoretical Biology*, 72, 1978, 191-204
[3] Wicken, J.S., Entropy gradient: A heuristic approach to chemical equilibrium. *Journal of Chemical Education*, 55, 1978, 701
[4] Wicken J.S., Self-organization vs. self-ordering events in life-origin models. *Journal of Theoretical Biology*, 77, 1979, 349-365.
[5] Morowitz, H., *Energy flow in biology*. Ox Bow Press, 1979.

[6] Nicolis G., *Physics of Far–From-Equilibrium Systems and Self-organization*; in Davies P. (Ed.), *The New Physics*; Cambridge University Press: New York, 1989.
[7] G. Nicolis and I. Prigogine, *Exploring Complexity. An introduction*, Piper, Munich, 1987.
[8] Pulselli R.M., Ratti C., Tiezzi E., City out of chaos: social patterns and organization in urban systems. *International Journal of Ecodynamics*, WITpress, Southampton, 1(2), 2006, pp. 125–134.
[9] Pulselli R.M., Pulselli F.M., Marchettini N., "The conjunction of non living and living in human systems: why do novelties emerge?", International Journal of Ecodynamics, WITpress, Southampton, 2(4), 2007, 245–249
[10] Tiezzi E., *Steps towards an evolutionary physics*; WITpress, Southampton, UK, 2007.
[11] Tiezzi E., *Beauty and Science*; WITpress, Southampton, UK, 2004.