R.E. Ulanowicz, Int. Journal of Ecodynamics. Vol. 2, No. 3 (2007) 153–164

ECOSYSTEMS BECOMING*

R.E. ULANOWICZ
Center for Environmental Science, University of Maryland, Chesapeake Biological Laboratory, Solomons, MD, USA.

ABSTRACT
Ilya Prigogine, through his pioneering insights into complex systems, 'established the basis for ecological systems research'. His interest in irreversibility at microscopic scales was a prelude to today's recognition of the key role that the aleatoric plays in macroscopic ecosystem behavior. With his theory of self-organization, Prigogine telescoped the need to consider processes in lieu of laws. His early work with variational statements about whole systems echoes still in today's principle of increasing ascendency for developing ecosystems. Most importantly, his theory of dissipative structures focused attention upon the nature of the agency most important to ecosystem behavior – configurations of mutually beneficent processes. Overall, his perspective on complex system dynamics eventually forced a needed revision of the metaphysical basis that supports the study of living systems.
Keywords: ascendency, autocatalysis, centripetality, dissipative structures, ecosystem, history in dynamics, irreversibility, process philosophy, self-organization.

1 FOLLOWING A LEGACY

Thank you Professor Brebbia for your gracious introduction.

Distinguished guests, Ladies and Gentlemen.

This is indeed a monumental day in my life, and there are so many to whom I am grateful that I could go on thanking friends and associates for most of my allotted time. I will instead mention but a few who are represented here today, beginning with my wife Marijka, my dear partner in life and in intellect, who stands in for my beloved family, both living and past. I am indebted as well to the previous recipients of the Prigogine Medal, to Professor Enzo Tiezzi, who is with us today and reminds us of Professors Sven Jørgensen and Bernard Patten, earlier laureates who could not attend these ceremonies, but who are dear friends and most esteemed collaborators. As some of you may know, the three of them have organized an informal colloquium of systems thinkers who are exploring exciting new approaches to ecosystem dynamics – a group that includes my colleagues Professor Joao Carlos Marques and Dr Joana Patricio of the University of Coimbra.

As Professor Brebbia mentioned in his opening remarks, the reason why we hold this ceremony each year is to celebrate the legacy of an individual who opened for us an entirely new vista on nature – Ilya Romanovich Prigogine. Perhaps more than most, I feel a particular indebtedness to Professor Prigogine, because during my graduate studies and well into my academic career, he was my primary intellectual role model – first as a chemical engineer and then as an ecologist. Now, if it should strike you that the transition from chemical engineer to ecologist is a peculiar one, the reason it was possible at all owes in large measure to Prigogine's ideas. Here I note that Prigogine himself began as a chemist and later transitioned into several other disciplines. Of particular interest to us today is Professor Brebbia's [1] statement at last year's ceremony 'Prigogine's ideas established the basis for ecological systems research.'

* An address delivered at the 2007 ECOSUD Conference, University of Coimbra, Coimbra, Portugal, 5 September 2005.

ISSN: 1743-5242 (paper format), ISSN: 1743-5250 (online), http://journals.witpress.com
DOI: 10.2495/ECO-V2-N3-153-164

Now, these are bold words, and truth be told, if one were to ask practicing ecologists exactly how Prigogine contributed to our understanding of ecosystems, the vast majority would respond with utter bewilderment. Few ecologists even know who Prigogine was, much less could imagine how he helped us to perceive ecosystems behavior more clearly. In my own case, however, Prigogine's notions have been fundamental to the treatment of ecosystems dynamics that I have developed over the last 37 years. To demonstrate the centrality of Prigoginian thought to my own worldview would require that I provide you with a full description of Prigogine's philosophy of nature in addition to a complete exegesis of my own hypotheses.

Time is not adequate to fully elaborate either of these subjects, much less both. And so I encourage you to read the excellent synopsis of Prigogine's life and work that the Wessex Institute has provided [2]. I then beg your indulgence as I refer to Prigogine's immense contributions in terms of well-known but superficial catch-phrases that people often apply to his work – words like 'irreversibility', 'self-organization', 'minimum entropy production', 'order through fluctuation', and 'dissipative structures'. In passing, I will mention only a few sentences about each of these subjects and then concentrate on what that idea generated in my own narrative on ecosystem dynamics. I hope, thereby, to convince you that Professor Brebbia was indeed correct – Prigogine's ideas do provide new approaches to ecosystems and to the world in general.

2 IRREVERSIBILITY

A major hobby horse in Prigogine's writings was irreversibility [3] – where does it come from? Is it real or illusory? These are very important questions, because until the mid-1960s all of physics had been predicated on reversible laws. A reversible event is one that exhibits no qualitative difference in either temporal direction. A convenient example is a video of the collision of two billiard balls. If the balls are elastic enough, one will not be able to discern whether the video is being played forwards or backwards.

Irreversible processes became a part of scientific narrative with Carnot's discovery of the second law of thermodynamics early in the 19th century. The second law challenged both Newtonian thinking and the atomic hypothesis, each of which is predicated upon reversibility. How could a collection of simple particles behaving according to reversible universal laws possibly produce irreversible behavior in the aggregate? The question occupied the best minds in science throughout the middle of the 19th century. A resolution of this paradox was finally proposed late in the century by Ludwig von Boltzmann, James Clerk Maxwell, and Josiah Willard Gibbs, who together constructed the discipline that came to be known as statistical mechanics. They portrayed irreversibility as a statistical feature of ensembles of many particles that is not apparent at the scale of the collision of individual particles, which take place according to the reversible laws of motion.

Prigogine (and Stengers [4]) was not satisfied with this resolution. He was convinced that irreversibility was other than an epiphenomenon of large collections of bodies, and was rooted rather in the fundamental dynamics by which particles interact. He searched diligently for breaks in the symmetry of action at the microscales.

Without commenting further on Prigogine's directions, we note yet another possibility that transcends the microscopic. Whenever a significant number of distinguishable objects is present in a system, the combinations among them escalate so rapidly that totally unique events begin to appear that violate the continuum assumption. This argument was given rigorous form by physicist Walter Elsasser [5], who estimated that the overwhelming majority of stochastic events in biology are *totally* unique, never again to be repeated. Elsasser's assertion sounds absurd at first, given the enormity and age of our universe, but it is surprisingly easy to defend. He noted how there are fewer than 10^{85}

elementary particles in the whole known universe, which is about 10^{25} nanoseconds old. (A nanosecond is one-billionth of a second.) Under these conditions, no more than 10^{110} simple events could possibly have occurred during all of elapsed physical time. It follows, then, that any event with less than 10^{-110} probability of re-occurring will never do so in another 14 billion years. The infinitesimal probability of its re-occurrence is simply a number outside the realm of physics.

Now, 10^{110} is a genuinely enormous number. It might surprise some, however, to learn that it doesn't require Avagadro's Number (10^{23}) of distinguishable entities to create a potential number of combinations that exceeds Elsasser's limit on physical events. It doesn't require billions, millions or even thousands. In fact, a system containing about 75 identifiable components will suffice! It can therefore be stated with utmost confidence that any event comprised randomly by more than 75 distinct elements has never occurred earlier in the history of the physical universe.

The implications of this threshold for ecology are tremendous. Because ecosystems are comprised of hundreds or thousands of distinguishable organisms, one is forced to reckon not just with an occasional unique event, but with *legions* of them. In ecosystems unique, singular events are occurring all the time, everywhere! Ecosystems are perfused with irreversible events that take place at the *macroscopic* level.

In order to apply probability theory to chance events, it is necessary that tokens of those events repeat at least several times, in order to estimate a legitimate frequency. Singular events, however, occur only once, never to be repeated. Any probabilities assigned to them are merely numbers that transcend physical reality. Furthermore, such singular events constitute actual holes in the causal continuum. Like Heisenberg uncertainties or the Pauli Exclusion Principle, such singularities are *necessary* features of nature in their own right and not epistemological gaps requiring further theoretical exegesis.

3 FROM BEING TO BECOMING

Unfortunately, Prigogine seems to have been unaware of Elsasser's threshold and remained preoccupied with physically indistinguishable microscopic elements. Hence, the didactic presence of macroscopic irreversibility had eluded his notice. All along, irreversibility had been playing out before his very eyes. Had he been aware of it, he would likely also have recognized a subsequent dilemma – namely that a world so saturated with novel events can overwhelm universal laws, rendering the source of order in the macroscopic realm ambiguous.

Elsasser's reasoning, guaranteed that *determinism* cannot be a universal characteristic of nature. Not that anyone is dispensing with physical laws, however. They remain inviolate. It's just inconceivable that any combination of the four laws of force and the two laws of thermodynamics could possibly suffice to cover all the possible changes amongst a complex system with, say, 35 loci for change. Rather, any particular parametric specification of those laws will satisfy a *very large* multiplicity of combinations. Hence, laws continue to constrain complex biological phenomena, but they fall short of being able to stipulate actual outcomes. The agency that determines results must involve more than just laws.

But, despite rampant, ubiquitous singularities, it is easy to observe order in the biotic realm. Whence does it arise? Is it, as most biologists would have us believe, the work of a homunculus-like molecular agency that directs the construction of the organism? As popular as that attitude is, I would like to believe that Prigogine would have found it (as I do) philosophically insufficient. I prefer to think that he immediately would have recognized where true agency in biotic systems lies, because Prigogine had always placed emphasis on processes over objects – a bias that has made him immensely popular with the school known as 'process philosophy'. He continually preached the need to shift focus 'from being to becoming' [6].

With all this talk about process, it behooves us to become more precise about the term. I would like to propose an operational definition as follows [7]:

> A process is the interaction of random events upon a configuration of constraints that results in a non-random, but indeterminate outcome.

To help illustrate this definition, I bring to your attention the simple, artificial example called Polya's Urn [8]. To perform this exercise as a physical process requires a collection of red and blue balls and an urn that initially contains one red ball and one blue ball. The urn is shaken and a ball is blindly drawn from it. If that ball is the blue one, a blue ball from the collection is added to it and both are returned to the urn. The urn is then shaken and another draw is made. If the ball drawn is red, it and another red ball are placed into the urn, etc. The first question that arises is, 'After a long sequence of such draws and additions, does the ratio of red to blue balls converge to any limit?' It is rather easy to demonstrate that after, say, 1000 draws, the ratio does converge to some constant, say 0.54591, as shown in Fig. 1. In other words, the ratio becomes progressively less random as the number of draws increases.

The fact that the ratio did not converge exactly to 0.5000 prompts a second question, namely, 'What would happen if the urn were emptied and the starting configuration recreated? Would a subsequent series of draws converge to the same limit as the first?' It is easy to demonstrate that it would not. After 1000 draws the second ratio might approach a limit in the vicinity of 0.19561 (Fig. 2). The Polya process is clearly indeterminate.

One eventually discovers that the ratio of balls becomes progressively more constrained by the actual sequence of draws that have already occurred. After still more experimentation, it gradually becomes clear that the limiting ratio for any long sequence of draws and replacements is uniformly distributed between zero and one, i.e. the ratio can approach any rational fraction.

For later reference, I note three important features of this artificial and simplistic process:

1. It involves chance.
2. It involves self-reference.
3. The history of draws is crucial to any particular series.

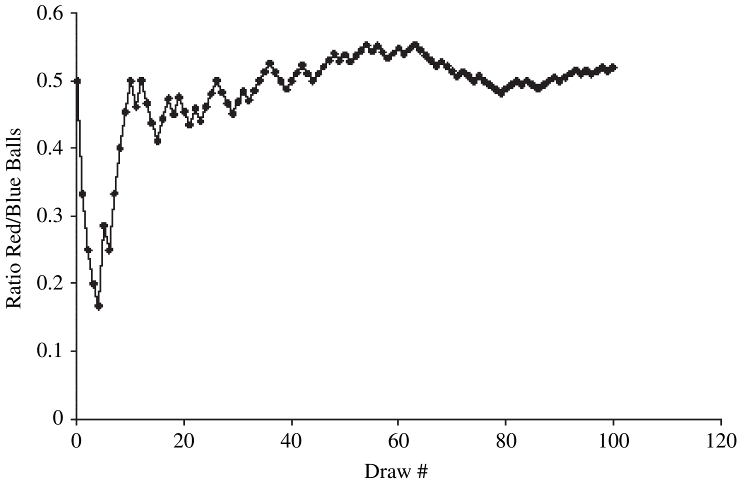

Figure 1: Polya's Urn, trial #1 after 100 draws.

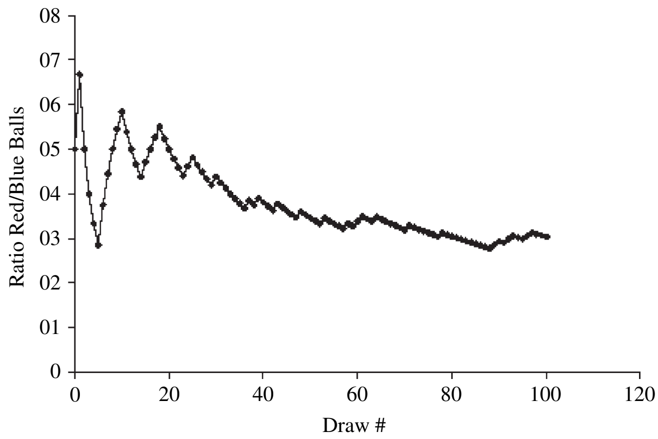

Figure 2: Polya's Urn, trial #2 after 100 draws.

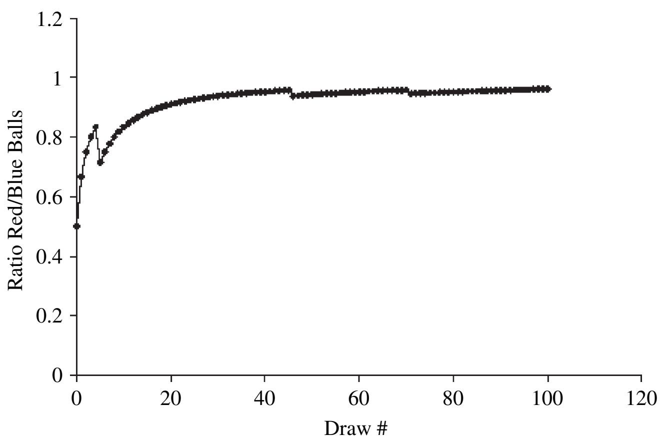

Figure 3: Polya's Urn, trial #3 after 100 draws.

We note further that some histories which converge to limits near zero or one are difficult to distinguish from mechanical, law-like dynamics exhibiting only occasional noise (Fig. 3).

Such mimicry raises the possibility that scientific laws may have evolved as limiting forms of earlier, less constraining processes.

4 AUTOCATALYSIS AND SELF-ORGANIZATION

So our focus now rests upon processes rather than laws. Still, Polya's Urn, while instructive, seems too simplistic and artificial. The transition to natural examples of processes would not have been a problem for Prigogine, because the notions of self-organization and autocatalysis were central to his lexicon [9].

It is important to note that autocatalysis is not a law, but rather a process, or more accurately a configuration of processes. Furthermore, Gregory Bateson [10] has suggested that natural processes could impart order to stochastic affairs. He noted in particular how the outcome of random noise acting upon a feedback circuit is generally non-random. I, therefore, draw your attention to Prigogine's favorite form of feedback – autocatalysis [11]. By 'autocatalysis' we mean here any instance of a positive feedback loop wherein the direct effect of every link on its downstream neighbor is positive (Fig. 4).

An illustration of autocatalysis at work in ecology is the community that forms around the aquatic macrophyte, *Utricularia* [12]. All members of the genus *Utricularia* are carnivorous plants. Scattered along its feather-like stems and leaves are small bladders, called utricles (Fig. 5a). Each utricle has a few hair-like triggers at its terminal end, which, when touched by a feeding zooplankter, opens the end of the bladder and the animal is sucked into the utricle by a negative osmotic pressure maintained inside the bladder. In nature, the surface of *Utricularia* plants is always host to a film of algal growth known as periphyton. This periphyton serves in turn as food for any number of species of small zooplankton. The autocatalytic cycle is closed when the *Utricularia* captures and absorbs many of the zooplankton (Fig. 5b).

The key feature of autocatalysis is that it can exert selection pressure upon any of its components or their attendant mechanisms. Any change in a characteristic of a component that either makes it more sensitive to catalysis by the upstream member, or a better catalyst of the element that it catalyzes, will be rewarded. Other changes will be neutral at best, but are more likely to be decremented by the feedback. In particular, this selection will re-enforce changes that bring more material or energy into any participating element, resulting in what can be called (in Newton's word) 'centripetality' (Fig. 6).

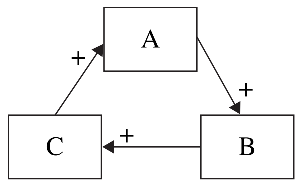

Figure 4: A three-component autocatalytic configuration of processes.

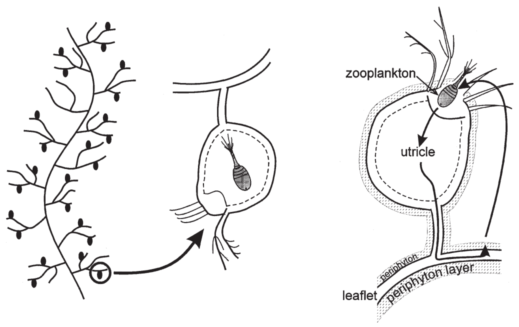

Figure 5: (a) Stem of *Utricularia* with close-up of utricle. (b) The autocatalytic processes inherent in the *Utricularia* system.

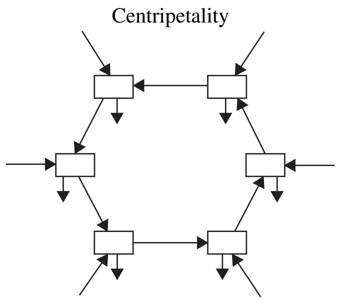

Figure 6: Autocatalysis induces centripetality.

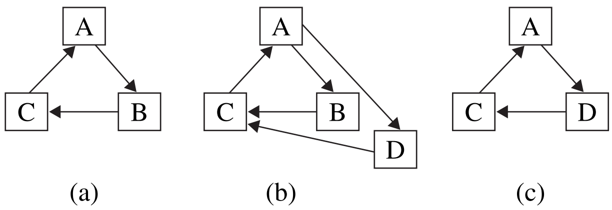

Figure 7: Centripetality induces competition.

It is difficult to overstate the contribution of centripetality to the phenomenon of life. Conventional Darwinism conveniently overlooks the role of 'striving' in evolution. All these various organisms are engaged in an epic struggle, competing with each other, red in tooth and claw. But what accounts for this drive? In other words, how do we demystify Darwinism? Here's what Bertrand Russell [13] had to say on the topic:

> Every living thing is a sort of imperialist, seeking to transform as much as possible of its environment into itself and its seed . . .. We may regard *the whole of evolution* as flowing from this 'chemical imperialism' of living matter. (Emphasis mine)

It is clear that by 'chemical imperialism' Russell is referring to centripetality, and he correctly places it at the very core of evolution.

Conventional Darwinism, to the contrary, points to competition as the crux of evolution. But in the new framework we see competition as *subsidiary* to centripetality (which, recall, rests upon notions of mutuality.) Thus, we recognize that competition cannot exist in the absence of mutual beneficence at some lower level.

Consider, for example, the sequence in Fig. 7. In the second configuration element D appears spontaneously in conjunction with A and C. If D is more sensitive to A and/or a better catalyst of C, then the ensuing dynamics of centripetality will so favor D over B, that B will either fade into the background or disappear altogether. That is, selection pressure and centripetality can guide the replacement of elements.

Of course, C could be replaced by E and A by F, so that in the long run, the lifetime of the autocatalytic configuration can exceed that of any of its components or their associated mechanisms. Such top-down influence decidedly violates the Newtonian axiom of *closure* – the assumption that material and mechanical causes acting together account for all of reality [14]. For that matter, the other assumptions that have guided science over the past 300 years are likewise contradicted by ecosystem behavior. Earlier, I indicated how *determinism* cannot pertain to complex systems. The unidirectional or asymmetric nature of autocatalysis makes a system highly *irreversible*. The fact that the development of each component is influenced strongly by its co-participants renders all system elements highly co-dependent over time, so that no organic complex is fully amenable to *atomistic* decomposition. Finally, no particular process is *universal*; each is circumscribed in time and space and subject to influence from processes at other levels.

5 MINIMUM ENTROPY PRODUCTION?

The compelling properties of autocatalysis all suggest that the process is absolutely central to the development of living systems. In fact, it is possible to quantify the degree to which autocatalysis actively affects a system. The measure is called the system's ascendency. Unfortunately, time does not allow me to detail how ascendency is calculated, but the net effect of autocatalysis is to emphasize those elements that participate in the process over and above non-participants, as shown in Fig. 8.

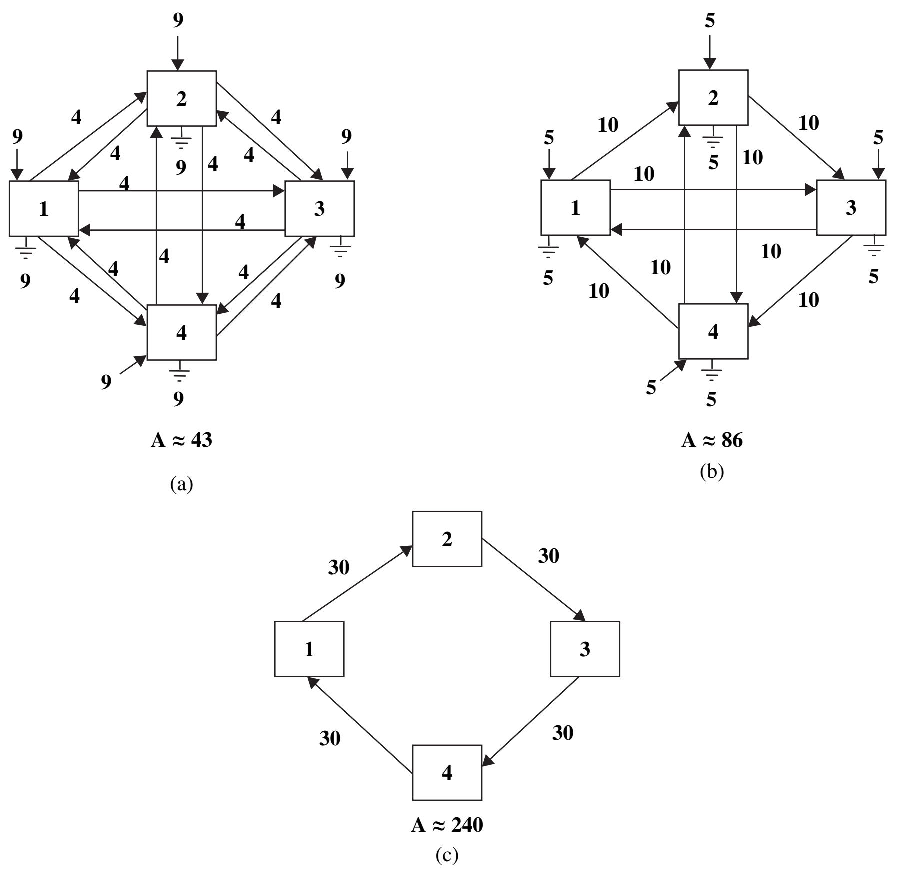

Figure 8: The progression of a hypothetical simple system: (a) a very inchoate configuration, (b) one more constrained by growing autocatalysis, and (c) the maximally constrained, autocatalytic configuration.

The tendency for autocatalysis to exert growing influence upon living systems prompted me to formulate the progression as a phenomenological principle [15, 16]:

> In the absence of major perturbations, ecosystems have a tendency over time to take on configurations of greater ascendency.

One notices immediately how this statement resembles a variational principle, i.e. a maximum/ minimum, or goal-seeking rule. The similarity is not surprising, given my early preoccupation with Prigogine's [17] thesis that systems near equilibrium produce entropy at a minimal rate. The idea that attributes of the whole system could influence behaviors at lower scales has always fascinated me.

But ecosystems are not merely physical systems, and my hypothesis is not strictly a variational statement, as reflected by the inclusion of the word 'tendency'. Living systems possess distinctly non-mechanical attributes, so that directionality in life is almost certain to be looser than the greedy goal-seeking that characterizes mechanical systems [18].

As it turns out, increasing ascendency is only half of the story. The countervailing half is the second law tendency for systems to degrade and dissipate over time. Most fortunately, the disorder inherent in the second law can be quantified using exactly the same mathematics (information theory) that was used to formulate ascendency, and I have called this complement the system 'overhead' [19].

6 ORDER THROUGH FLUCTUATIONS

The common observation is that the agencies that build order are openly antagonistic to the tendency to dissipate structure – the yin and yan of nature. This is not the full picture, however, because what appears to be antagonism at one scale can appear mutualistic at another. Prigogine [9] implicitly recognized this Hegelian aspect of the natural dialectic in his theory of 'order through fluctuations'. In his mathematical models of bifurcated dynamics, Prigogine suggested that macroscopic form could depend strongly upon the history of microscopic fluctuations that have impinged upon a system while it had been in a dynamically metastable state. Restating his conclusion backwards – increasing order becomes impossible without the action of stochastic, otherwise disordering events.

In Prigogine's model one perceives an inchoate version of the full scenario of development in living entities as we now envision it. Systems are constantly being impacted by a veritable rain of singular events, which can occur at *all* levels of scale. Feedback controls, however, are also at work at all levels to ameliorate the impacts of almost all of them. Only a very small minority of aleatoric disturbances will succeed in altering the system; but the controlling feedbacks are usually able to contain these impacts. In exceedingly rare instances, complex disturbances will match hand-in-glove with vulnerable systems junctures to drive the system into a new, *emergent* mode of behavior.

7 DISSIPATIVE STRUCTURES

The emphasis that Prigogine gave to processes draws us out of our obsession with the omnipotence of laws. Furthermore, it is becoming increasingly obvious that not all agencies behind change in living systems are objects. The intricacies of autocatalysis shift the spotlight to *configurations of processes* as the dominant causalities that sustain life. This view owes much to Prigogine's notion of dissipative structures, for which he was awarded the Nobel Prize in Chemistry in 1977.

To drive home the importance of how action can be elicited by patterns of processes, I cite the example of a deer that has just been shot by a hunter. Professor Tiezzi [20] in his recent book, *Steps Towards an Evolutionary Physics*, asks what is missing in the dead deer that had been present in the minutes before its demise. Its mass, form, bound energy, genomes – even its molecular configurations – all remain virtually unchanged immediately after death. What had ceased with death and is no longer present is the *configuration of processes* that had been coextensive with the animated deer – the very agency by which we recognize the deer as being alive.

8 FROM BEING TO BECOMING (REDUX)

Earlier, I commented on how ecological behaviors violate each and every one of the five postulates of Newtonian dynamics that have supported science in one form or another over the past 300 years [21]. With our emphasis now on processes and configurations of processes, as initiated by Prigogine, we are forced to seek a *new* set of fundamental assumptions. We are driven to formulate an ecological metaphysics, if you will.

Obviously, these new axioms must be related to the notion of process as I have defined it, and here I ask you to recall the three attributes of that simple example, Polya's Urn – namely chance, feedback, and history.

Concerning chance, our first assumption is to recognize it as an ontological reality and not simply as an illusion, i.e. nature is causally open. It exhibits

1. *Radical contingency*: Nature in its complexity is rife with singular events.

Although the destructive effects of chance are usually what is immediately apparent, one must never lose sight of the requirement that true change can never arise in a world that lacks contingent events.

Opposing the degradation by chance action is the constructive process of autocatalysis, a particular form of self-influence, which works to impart form and pattern to nature. Accordingly, our second postulate focuses upon feedback as the dominant agency that builds and sustains living systems.

2. *Self-influence*: A process in nature, via its interaction with other natural processes, can influence itself.

This assumption releases us from the requirement of having to cast all explanation in a reductionistic format.

Thirdly, we recognize that the interaction between chance and feedback leads nowhere without some record of past system configurations. That is, as Darwin [22] posited, living entities must possess a

3. *History*: The effects of self-influence are usually constrained by the culmination of past such changes as recorded in the configurations of processes and matter in living entities.

In today's scientific milieu, dominated as it is by reductionistic thought, we immediately think of DNA and similar material forms as the repositories of history. As we saw with our remarks on competition, however, the first recordings of organic history were more likely written into the topologies of long-lived interacting processes.

9 HUMANITY'S DIALOGUE WITH NATURE

Upon these three axioms one can build in logico-deductive fashion a full narrative of living behaviors. I have called the ensuing construct 'process ecology' [23]. Because each of the three postulates contradicts one or more of the classical Newtonian assumptions, it should come as no surprise that process ecology departs radically from conventional constructs, such as neo-Darwinism. The actions I have described, such as internal selection, top-down influence, and emergence, are outright heresies to the received wisdom, but they rest quite comfortably within the ecological metaphysic.

I will not pretend that if Ilya Prigogine were in the audience today, he would applaud all that I have suggested. Those of you who remember him will certainly recall his ardor in rebutting anyone who would suggest the slightest deviation from the pathway he believed nature was following. Doubtless, he would be livid at some of the departures I have made. None of which detracts from the enormous debt that I and my fellow systems ecologists owe him for pioneering such bold and radical new approaches to the phenomenon of life.

Prigogine (and Stengers [24]) subtitled what was perhaps his most famous book, 'Man's (sic) New Dialogue with Nature'. There is no mistaking that his challenge to the conventional metaphysics that had bound humankind with the chains of all-determining physical laws truly liberated us to adopt a wholly new perspective on the natural world. His ideas also changed attitudes in a way that could lead to a healthier, more constructive dialogue between C.P. Snow's [25] two cultures – the sciences and the humanities. His ruminations on the production of entropy even provide a glimmer of hope that the final scenario for the cosmos might be other than what has been termed 'heat death', and thereby rescue us from the prevailing 'cosmology of despair' [26]. His focus on process and activity was a welcome diversion from what Hans Jonas [27] has described as an 'ontology of death'.

But in the end it must also be said that the portal to hope lies not with Prigogine's beloved physics, nor within the chemistry for which he was lauded. It now appears that hope truly looms into view only after one has passed through the gateway that we call ecology.

I thank you for your kind attention.

REFERENCES

[1] Brebbia, C., Opening address, *The Sustainable City 2006*, Wessex Institute of Technology, Ashurst, Southampton, UK. http://www.wessex.ac.uk/conferences/2006/city06/index.html, 2006.

[2] Wessex Institute, *Autobiography of Ilya A. Prigogine (1917–2003), Winner of the Nobel Prize in Chemistry 1977*. http://www.wessex.ac.uk/conferences/2007/prigogine/callforapplications/autobiography1.html, 2007.

[3] Prigogine, I., *Is Future Given?* World Scientific: River Edge, NJ, p. 145, 2003.

[4] Prigogine, I. & Stengers, I., *The End of Certainty: Time, Chaos, and The New Laws of Nature*, Free Press: New York, p. 228, 1997.

[5] Elsasser, W.M., Acausal phenomena in physics and biology: a case for reconstruction. *American Scientist*, **57**, pp. 502–516, 1969.

[6] Prigogine, I., *From Being to Becoming: Time and Complexity in the Physical Sciences*, W.H. Freeman: San Francisco, p. 272, 1980.

[7] Ulanowicz, R.E., *A Third Window: Natural Foundations for Life*, Oxford University Press: Oxford (in press).

[8] Cohen, J.E., Irreproducible results and the breeding of pigs. *Bioscience*, **26**, pp. 391–394, 1976.

[9] Nicolis, G. & Prigogine, I., *Self-organization in Nonequilibrium Systems: From Dissipative Structures to Order Through Fluctuations*, Wiley: New York, p. 491, 1977.

[10] Bateson, G., *Steps to an Ecology of Mind*, Ballantine Books: New York, 1972.

[11] Ulanowicz, R.E., *Ecology, the Ascendent Perspective*, Columbia University Press: New York, p. 201, 1997.

[12] Ulanowicz, R.E., *Utricularia*'s secret: the advantage of positive feedback in oligotrophic environments. *Ecol. Model.*, **79**, pp. 49–57, 1995.

[13] Russell, B., *An Outline of Philosophy*, Meridian Books: Cleveland, OH, 1960.

[14] Clayton, P., *Mind and Emergence: From Quantum to Consciousness*, Oxford University Press: New York, 2004.
[15] Ulanowicz, R.E., An hypothesis on the development of natural communities. *J. Theor. Biol.,* **85**, pp. 223–245, 1980.
[16] Ulanowicz, R.E., *Growth & Development: Ecosystems Phenomenology*, Springer-Verlag: New York, p. 203, 1986.
[17] Prigogine, I., Moderation et transformations irreversibles des systemes ouverts. *Bull. Classe Sci., Acad. Roy. Belg.*, **31**, pp. 600–606, 1945.
[18] Mueller, F. & Leupelt, M., *Eco Targets, Goal Functions, and Orientors*, Springer-Verlag: Berlin, p. 619, 1998.
[19] Ulanowicz, R.E. & Norden, J.S., Symmetrical overhead in flow networks. *Int. J. Systems Sci.*, **1**, pp. 429–437, 1990.
[20] Tiezzi, E., *Steps Towards an Evolutionary Physics*, WIT Press: Southampton, 2006.
[21] Ulanowicz, R.E., Life after Newton: an ecological metaphysic. *BioSystems*, **50**, pp. 127–142, 1999.
[22] Darwin, C., *On the Origin of the Species by Means of Natural Selection*, or *The Preservation of Favoured Races in the Struggle for Life*, J. Murray: London, 1859.
[23] Ulanowicz, R.E., Ecosystem dynamics: a natural middle. *Theology and Science*, **2(2)**, pp. 231–253, 2004.
[24] Prigogine, I. & Stengers, I., *Order Out of Chaos: Man's New Dialogue with Nature*, Random House: Boulder, CO, p. 349, 1984.
[25] Snow, C.P., *The Two Cultures and the Scientific Revolution*, Cambridge University Press: New York, p. 92, 1963.
[26] Haught, J.F., *God After Darwin: A Theology of Evolution*, Westview Press: Boulder, CO, 2000.
[27] Jonas, H., *The Phenomenon of Life*, Harper and Row: New York, 1966.