Downward Causation: Polanyi and Prigogine

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ABSTRACT

Michael Polanyi argues that in the case of both organisms and machines the functionality of the higher level imposes boundary conditions that harness the operations of lower level components in the service of the higher level, systemic whole. Given the science of his day, however, Polanyi understands this shaping of boundary conditions in terms of the operation of an external agency. The essay argues that the science of nonlinear, far from equilibrium thermodynamics in general, and the phenomenon of autocatalysis in particular, explains how the endogenous closure of context-sensitive dynamic constraints shapes their boundary conditions such that self-organized, causally effective properties emerge.

It has been nearly forty-five years since Michael Polanyi's "Life Transcending Physics and Chemistry" and "Life's Irreducible Structure" appeared in *Science* and *Chemical & Engineering News* and are now available in *SEP* and *KB*, respectively. Over thirty-five years have also passed since Ilya Prigogine became a Nobel laureate in Chemistry for his discovery of dissipative structures. That same year, 1977, Prigogine coauthored (with Gregoire Nicolis) *Self-Organization in Non-Equilibrium Systems*, Prigogine's first book extending the concept of dissipative structures from physical thermodynamics into the biological realm. I would like to take the opportunity of these anniversaries to explore the role of boundary conditions in complex systems—in particular, how boundary conditions come into existence and are causally effective.

In "Life's Irreducible Structure," we find the following descriptions of the operation of boundary conditions on components: top-down (to use our terminology), each [level] "*reduces the scope* of the one immediately below by *imposing* on it a boundary that *harnesses* it to the service of the next higher level, and this *control is transmitted* stage by stage to the basic inanimate level" (*KB*, 234, emphasis mine). I cite this sentence in particular because the verbs *reduces, imposes, harnesses* (or their cognates) appear often in this piece—and elsewhere in Polanyi's writings—along with *integrates, comprehends,* and others. These terms refer to the *operation*s of downward causality. But the *operation* of boundary conditions is one thing; the *origin* of those boundary conditions is another. For that subject Polanyi uses the verbs and phrases such as *bring into existence, come into existence, emerge into existence,* or even *how it is that such structures can exist,* in contrast to the more commonly used verbs *control, shape*, and similar cognates which refer to the *operations* of those boundary constraints, not their *origin*.

How are boundary conditions established? Polanyi explicitly states that "*shaping* boundaries goes beyond a mere 'fixing of boundaries'"; [it] establishes a "controlling principle," a constraint that works in virtue of the boundary conditions' *pattern*. In Polanyi's words, this patterning establishes "a *significant distribution of matter* not determined by the laws of chemistry" (*SEP*, 294, emphasis mine),a distribution that embodies a particular pattern.[1] Once this structuring pattern is in place, it controls, harnesses, etc.—in other words, constrains—the constituents of the pattern such that they carry out a function in the service of the pattern, that is, to maintain the pattern. The pattern serves as a semantic interface between the two levels insofar as it warrants describing the parts as functional or otherwise. Boundary condition shaping therefore places "the system under the control of a non-physical-chemical principle by means of *a profoundly informative intervention*" (*SEP*, 295).

It is not difficult to describe how fixing boundaries comes about in artifacts and machines. When humans design and manufacture machines they arrange and organize raw materials such that the resulting pattern and shape subsequently constrains matter and energy flowing through those boundaries. Humans effect that shaping by culling and modifying materials—reducing their state space—according to the intended function of the to-be-built machine. The desired function in light of which humans carry out the shaping provides the informational interface for the process. Suitably channeled, flows of matter and energy within that system thus carry out the intended function for which the designer created and manufactured the machine in the first place. I want to highlight the *externality* of the designer/manufacturer agent responsible for the bringing into existence the patterning of matter that constitutes the machine. In the case of machine design, manufacture and functioning, that is, and operating from the outside and before anything else happens, an intelligent designer fixes certain boundary conditions by selecting from among the available materials and thereby channeling the energetic and material flow through the suitably arranged parts.

But what about living things? "When I say that life transcends physics and chemistry," Polanyi explains, "I mean that biology cannot explain life in our age by the current workings of physical and chemical laws" (*SEP*, 294-295). Why? Because according to the chemistry and physics of the day (what, following Michael Lissack,[2] I will call Science 1.0),

> *no level can gain control over its own boundary conditions* and hence cannot bring into existence a higher level, the operations of which would consist in controlling these boundary conditions. Thus the logical structure of the hierarchy implies that a higher level can come into existence only through a process not manifest at a lower level, a process which *thus* qualifies as an emergence (*TD,* 45, emphasis mine).

A few pages later, Polanyi adds, "The first emergence, by which life comes into existence, is the prototype of all subsequent stages of evolution, by which rising forms of life, with their higher principles, emerge into existence" (*TD,* 49). Elsewhere, Polanyi reiterates this point by stating that "any particular application of such a [general] principle requires that these circumstances be fixed by some agency not under the control of that principle" (Wesleyan V-4). Mullins interprets this phrasing to mean that the "the boundary conditions of the system to which the law of physics is applied" are the "conditions which have to be fixed by an *external* agency."[3]

So at least with respect to these comments concerning boundary conditions and their application, the general principle at work in the case of living things remains the same as in machines: an external agent is required to fix or shape the boundary conditions that enable life to appear. Aside from the fact that principles governing the isolated particulars of a lower level *leave indeterminate* conditions at the lower level—properties of lower level components allow for the possibility of hierarchization—it is nevertheless the case that a process *other than* operations at the lower level is what shapes the boundaries within which the higher level can emerge. Even when a whole and its components are acknowledged as constituting one hierarchically differentiated entity, *the agency that brings about* the conditions that enable hierarchy's emergence are held to be external.

As ahead of his time as Polanyi may have been, the Owl of Minerva of today's nonlinear complex dynamical systems theory had not yet spread its wings. So, in apparent contradistinction to other of his positions, at least for purposes of the topic of the origin and operation of boundary conditions, Polanyi presumes several ontological principles. These include:

- The claim that only efficient causes are real (a modernist principle);
- the two Aristotelian principles that:
    1. nothing can cause itself [4] and
    2. there must be as much reality in the cause[5] as in the effect;
- the two principles inherent in atomist metaphysics, particularly as interpreted by Newtonian mechanics, that
    1. only those essential properties that inhere in those individuals and that define universals are real, and
    2. relations and other so-called 'secondary qualities' are subjective and merely epiphenomenal.

In *Dynamics in Action*, I tried to highlight the impact that this set of assumptions had on philosophical action theory during its heyday from the 1960s through the 1980s. Among the most egregious consequences is that together they render mereological causality—the mutual interactivity between parts and wholes—paradoxical at best, incomprehensible at worst.[6] As a result wholes are either uncritically relegated to the status of mere epiphenomena, pragmatic, heuristic labels with no ontological purchase; or paradoxical in the mode of Plato's Cretan Liar or barber paradoxes attributed to Russell, the only way out of which is the path even Russell takes: to insist that in fact, one part of a whole acts on another part, which acts on another, etc.[7] But to retain the Aristotelian principle that no whole exists or acts as such because nothing can act on itself (the first disjunct again), in conjunction with the thesis that the only type of cause is efficient causality, renders all wholes mere epiphenomena. With respect to the specific topic of boundary conditions, it means that boundary conditions cannot be self-produced.

In other words, with the dismissal of formal and final causes and the reduction of all exercise of causal power to efficient causality in the form of forceful impact of atomic entities,the accepted metaphysical stance was that individual particles cannot create truly novel wholes themselves and wholes cannot modify the particles that make them up.[8] True emergence, any form of radical novelty and creativity such as we will see in autopoiesis, therefore, becomes a logically inconsistent notion—only development is possible (Depew & Weber, 1995). And allowing chance to play a role, as in Darwin's mutations, just complicates matters even further—and I am not even addressing problems with the standard deductive-nomological account of explanation advocated by mechanistic Science 1.0. Once Aristotle's notion of *phronesis* was discarded and only *episteme* and *theoria* are allowed as scientific, appeals to random mutations disqualified any such purported explanations from the realm of science.

Accordingly, the accepted meaning of the term *evolution* at the time of Polanyi's writing still generally adhered to a Spencerian understanding of that term, the unfolding of pre-established potentialities, not radical novelty. Top-down, the Darwinian understanding of the environment is that of a passive container—round pegs don't reproduce successfully in square niches, so over time that phenotype dies off, but niches aren't active in any real sense. Niches are, at best, epiphenomena. Polanyi follows this understanding of evolutionary change (at least in "Life's Irreducible Structure") when he allows that although the higher levels "may be present in traces" they must not be "altogether absent" before they become "prominent" (*KB*, 234). Polanyi's preformationist description of development in this passage, is therefore of a type of "intensification…which is what we witness in the development of the embryo" (*KB*, 232). But it is obvious that Polanyi is tentatively groping towards an expanded notion of development that would allow boundary conditions to be self-caused in some way. Intensification is not to be conceptualized along the lines of blueprint implementation; development is the *evocation* or *eliciting*. However, the actual evocation or eliciting of a higher level comes from the outside, from atomic or molecular accidents (presumably random mutations. See *KB*, 235).

I want to argue that nonlinear dynamical systems theory has given us a way of understanding how recursive dynamics can endogenously bring about boundary conditions without the intervention of an external agent.

It was that in late Fall 1984 that I found myself reading Kant's *Critique of Judgment* during the same week I purchased Prigogine and Stengers's recently published (in English) *Order out of Chaos.* Immanuel Kant, of course, had realized early on that the Newtonian understanding of cause could not render tractable the intrinsic teleology of living things. As an example, Kant cites a tree, which produces leaves at the same time as it is produced by those leaves. In living things, that is, Kant recognized a recursive type of causality wherein the effect is a necessary condition for bringing about the cause that in turn produces that very effect. But since this kind of causality is absent from both Newton's mechanics and Hume's analysis of causal relationships, it is, Kant regrets, "unknown to us." He could only relegate the appearance of such intrinsic teleology to the "regulative (subjective) judgment;" it can play no role in the constitutive judgment of synthetic *a priori* epistemology.

But the causal power of boundary conditions is precisely what Prigogine's work on dissipative structures highlights. In particular, Prigogine showed how boundary conditions play a role in creating order and structure out of disorder and chaos. Bénard cells are good examples of physical dissipative structures. Heating a pan of water uniformly from below creates a temperature gradient between the cooler water on the top and the warmer water at the bottom. This disequilibrium, if increased beyond a particular point, eventually results in a bifurcation or phase transition; a macroscopic structure of rolling hexagonal convection cells composed of billions of molecules of water suddenly emerges. *Structure*, Polanyi's "pattern," thus emerges where there was none before, and it comes into existence in open far from equilibrium thermodynamic processes as a result of the interaction between the bottom up energetic flows and the boundary conditions of the pan's edges and the external heat source. Order, an ontological emergent, appears out of chaos.

Once caught up in a rolling hexagonal Bénard cell, the behavior of individual water molecules is altered. Its degrees of freedom are now restricted so as to maintain the rolling hexagonal convection pattern.[9] The behavior of the individual water molecules is shaped, controlled, restricted by the "pattern" of the higher level organization—indeed, the boundary conditions—of the rolling water cell in which the individual molecule is captured. As noted earlier, Polanyi often employs the term "pattern" to describe the higher level of organization that controls the lower level operations. He states: "We can now see more clearly why such shaping of boundaries may be said to go beyond a mere 'fixing of boundaries' and establishes a 'controlling principle.'" Boundary fixing creates a controlling principle—a constraint, in my vocabulary—by "imprinting a significant pattern on the boundaries of the system" (*SEP*, 294).

In the case of Bénard cells, an external agency is responsible for that boundary fixing: one can point to either the shape of the pan or the scientists themselves who set up the experiment and select the shape and size of the pan in which the water is poured, and who supply the heat that results in an energy gradient, and continues to increase the temperature to the critical threshold. So the analogy between machine and physical dissipative structures suggested by Polanyi holds on both counts when it comes to characterizing their boundary conditions: a Bénard cell cannot be explained solely in terms of bottom-up energetic considerations; and boundary conditions set by an external agency play a critical role in bringing about higher level organization.[10] But this is true of all open, nonlinear, far from equilibrium physical processes.

So Prigogine's discovery of dissipative structures, I would argue, takes Polanyi's revolutionary pairing of machines and living things one step further by carving up nature at an even more encompassing set of joints, defining an ontological classification that includes dust devils, tornadoes, and Bénard cells in the same category as machines. In each case the boundary conditions actively shape/control/regulate the component parts; and in both machines and ***physical*** dissipative structures in general the boundary conditions are "set from without."

But one finds another principle at work in open, nonlinear, thermodynamic processes far from equilibrium from the stage of ***chemistry*** onwards. The "go of things," as Peirce would say, changes qualitatively once we reach the level of chemistry, which I suspect is why so many articles about the topic of emergence (such as those by Peirce and Polanyi) were either first published in chemistry journals or otherwise refer to examples from chemistry. It might also be the reason why Prigogine follows up his discovery of dissipative structures with an exploration of nonequilibrium systems in general to include first ***autocatalysis*** and then living things, both of which are classified as dissipative structures as well. To be sure, far from equilibrium, complex dynamical systems, including living things, are always and necessarily open systems. In the end, the only closed system is the universe, and so the ultimate fixer of boundary conditions on earth is the sun's energy. Nevertheless, the manner in which boundaries are fixed in chemical autocatalysis and in the earlier physical dissipative structures such as Bénard cells or dust devils is qualitatively different.

Autocatalytic processes rely on the mutually reinforcing dynamics of several positive feedback steps. The Belousov-Zhabotinsky reaction is a dramatic example. Schematically,

$$A \rightarrow X$$
$$B + X \rightarrow Y + Q$$
$$X \rightarrow P$$
$$Y + 2X \rightarrow 3X$$

What is unusual in this example is that the fourth step in the reaction is autocatalytic: one of its products is necessary for the activation of the product itself. As more and more X is produced by this recursively interactive set of reactions, the resulting nonequilibrium reinforces the runaway cycle unleashed by the endogenous dynamics themselves. At a critical threshold far from equilibrium, a small randomly occurring fluctuation can no longer be damped; instead those same dynamics amplify it, thereby driving the reaction across a bifurcation threshold—across a phase transition—to a new mode of organization. In the case of the B-Z reaction, a chemical wave that oscillates from blue to red suddenly appears, an emergent macroscopic pattern that embodies the coherent, synchronized behavior of millions of individual chemical components. Note what makes all of these examples of nonlinear, far from equilibrium thermodynamics: in each case, a thermodynamic gradient reaches a critical threshold where a random fluctuation is amplified, driving the system over the bifurcation into a new level of organization marked by the emergence of a new macroscopic structure—a metastable *pattern* of relationships—embodying the coherent, coordinated behavior of previously independent particles. This new macroscopic regime exhibits novel properties that cannot be reduced to the aggregation of the properties of the component parts. Polanyi's characterization of "chance fluctuations…releas[ing] the action of an emergent, 'self-sustaining' reality" is most apposite here. However, his evaluation of non-living emergents as "comparatively poor in new features" (*PK*, 394), is not. I would like to point out that one finds a crucial new feature even in these chemical processes: the emergence of a proto- top-down causality.

The qualitative difference between physical dissipative structures and autocatalytic chemical ones is dramatic: in the latter, it is the closure of an endogenous chain of positive feedback processes (A -> B -> C -> D ->… back to A), not an external agent, that creates the boundary conditions within which the macro-systems level self-organizes. What is important is that these macroscopic emergent dynamics are not "other than" the operations of the lower level—they ***are*** the operations of the lower level, now newly or differently constrained. There is no external agency that shapes or patterns the boundary conditions as occurs in physical Bénard cells or machines. In chemical autocatalysis it is the constraint dynamics of the four steps in the B-Z reaction themselves, working in a mutually recursive loop, that create the boundary conditions within which the emergent chemical wave self-organizes. This is why autocatalysis is usually viewed as the locus of the emergence of *autonomy* or *autopoiesis*. as opposed to the mere self-maintenance of physical dissipative structures given the external setting of boundary conditions. So there is, I would submit, a significant qualitative difference between physical and chemical forms of self-organization, but insofar as understanding the mechanisms of the former enables us to naturalize the latter, an appreciation of nonlinear thermodynamics even at the physical level constitutes a significant advance from the time of Polanyi's writings. Even physical dissipative structures allow us to appreciate how structure and pattern appear as a result of the interplay between the particulate level and the boundary conditions, a pattern that then loops back onto those constituents and affects their subsequent behavior. Autocatalysis in turn allows us to naturalize the notions of autonomy and self-cause. The thesis I defended in the 1985 *Review of Metaphysics* article on Kant and Prigogine is that the dynamics of context sensitive constraints exemplified by autocatalysis makes the concept of self-cause scientifically respectable and provides an account of mereological causality that allows a rethinking of both formal cause and intrinsic teleology.

Multiple realizability comes into its own at the level of chemistry.[11] Bénard cells, the example we used of physical dissipative structures, are composed of zillions of individual molecules of water, but each molecule of water is for all practical purposes identical to the next. As Moreno and Mossio (Springer, forthcoming) point out, there are only minimal constraints operating in physical dissipative structures. Not so in autocatalysis, which consists in various types of molecules and several constraints linked together in a concatenated set of reactions that closes back on itself. I would even go further. With autocatalysis we see the ontological emergence of a strong ***type-token distinction***. By definition each *type* can be embodied (enacted) in various different tokens. Moreno and Mossio (Springer, forthcoming) claim that truly *autonomous* self-organization takes place only in those cases where the closure of several recursively interacting constraints occurs. A catalytic function's multiple realizability—any given functional type can be instantiated by any number of particular token arrays—the emergence of *degeneracy*, and the corresponding emergence of a proto-adaptability at the level of chemistry already loosens strict determinism as the higher level assumes control of the "go of things" and can alter its own structure by selecting a particular microarray that will embody the overall function in particular circumstances.

It goes as follows: an autocatalytic triad ABC embodying function ***f*** can prune or discard component C and replace it with component D (Ulanowicz, 1990, 1997). Over time a given autocatalytic structure ABC might therefore eventually evolve into DEF all the while carrying out the "same" autocatalytic function ***f***. In philosophical terms, the selection is performed, not in terms of energetic requirements; rather ***it is performed according to criteria established at the higher level (according to the degree of fitness or functionality)***—a paradigmatic example of strong or radical emergence's characteristic feature: top-down causation (Fromm).[12] Since molecule D is selected in preference to C (which is discarded) because of the former's improved functionality, a certain proto-normativity also emerges for the first time insofar as the global system selects D on the basis of its "better" functional fitness. Autocatalysis allows us to understand the emergence of whole-part causation as well as the origin of normativity.

So autocatalysis provides evidence of the emergence of a qualitatively different ***type*** of constraint, from whole to part, that is central to autonomy, and that appears as a result of the closure of context sensitive constraints. Autocatalysis, as an example of the closure of context-sensitive constraint, therefore marks the first appearance of the *normative* selection process that Polanyi claims does not appear until living things.

Since the selective process just described is clearly not an example of efficient causality, how would this kind of bottom up and top down causality work? What I attempted to do in *Dynamics in Action* (1999) was to cash out this kind of causality as the workings of *constraint*, a concept which physicists and mechanical engineers have long been accustomed to deploying. Constraints too, play a role in communications technology and information theory, and although I fully recognize that information transmission is understood in terms of quantity of bytes and not semantic *content*, following Lila Gatlin, I suggested that we can nevertheless understand the redundancy implied in information-theoretical constraints as comprising two sorts: ***context-free constraints***, which like the distribution of letters in an alphabet take the system far from equiprobability by altering their probability distribution;[13] and ***context-sensitive constraints***, which like syntactic rules take a system far from independence.[14] Context-sensitive constraints are the mechanism that establishes long-range correlations, which changes everything.

Because context-free constraints quickly reach a bottleneck, complexification requires context-sensitive constraints. Catalysts and feedback as well as syntactical rules are examples of *first order context-sensitive constraints*. The long-range correlations these interactions effect, particularly under conditions of closure, constitute radical ontological novelty possessed of causal power. They are not simply the rearrangements of the existing furniture of the world, or the eliciting or evoking of existing but unrealized features. What context-sensitive constraints do is alter probability distributions—a topological renewal. *Given* the presence of context-sensitive constraints, other events become more or less likely than under the earlier topological regime, both synchronously and diachronically. Because a higher level of organization emerges as a result of the long-range correlations established by the closure of context-sensitive constraints, these are indeed enabling, not restrictive, constraints; they expand a system's phase space. The *coherent integration* characteristic of organisms is thus due to the *closure of first order context-sensitive constraints* and the establishment of these long-range correlations. There is no need to imagine a different substance emerging; nor is there any need to postulate an external agency that shapes the boundary condition patterning that resculpts the state or phase space, the terrain. The emergent coherent organism, I claimed in *Dynamics in Action*, ***is*** the altered probability distribution, in an expanded phase space—the renewed dynamic potential—of the lower level component operations. The emergent patterns and shapings Polanyi insists upon *are* the causally effective, if not efficiently causal, renewed probability distribution of those components. A new probability distribution of a relational pattern is what defines or ***constitutes*** higher levels of organization, and it is the new probability distribution that is endogenously fixed or shaped by the dynamical closure of first order context sensitive constraints.

Viewing things from this perspective allows us to appreciate that boundary conditions (boundaries) function not as walls, but as "active sites," like *eardrums* or *membranes* (Cilliers, 2002). Boundary conditions are not walls that keep the outside world out and the inside in; by interacting with what might have formerly been "outside," dynamical systems produce novelty by creating long-term correlations so as to incorporate, or embody, that outside—which now becomes part of (inside) the macro-dynamical system. Dynamical boundaries or boundary conditions are thus *interfaces* whose ontology cannot be separated from their two aspects: an inside and an outside. The two aspects of boundaries, the inner and the outer, correspond to Polanyi's insight concerning *from/at* epistemological perspectives, but the point I'm trying to make here is an ontological one: that the symmetry break occurs thanks to closure of context-sensitive feedback and that the radical emergent is the newly formed relational, hierarchically differentiated whole, which, in turn, is not ***other than*** the lower level in any sense of substance or efficient causality. From the complex dynamical systems perspective, then, mind and body are not "two different things" as Polanyi claims (*KB*, 238), but decoupled levels in a hierarchically differentiated dynamics.[16] The question of whether whole-part causality violates the laws of conservation suddenly dissolves. What has changed is that mereological causality has been revitalized and higher levels of organization therefore given their ontological—and causal—due.

The concept of downward causality can therefore be reconceptualized as the operation of second-order top-down constraints. Once again, the operation of autocatalysis provides a respectable scientific example of the closure of first order context-sensitive constraints. Once closure of first order top-down constraints occurs, the dramatic phase change that creates the higher level of organization—the systemic meta-level—also produces properties and behaviors that are absent from the components individually; nor can these properties be deduced from the sum of the components. The emergent higher level's organization controls, constrains, and harnesses, i.e., regulates top down the operations of the lower level by restricting the previous phase space of the independent components so that the emergent higher level's integrity, qua higher level, is maintained and enhanced. Once entrained or synchronized (self-organized) into a system, the dynamics of the lower level are constrained so as *to enact* the higher-level properties. By evolving as described above, complex dynamical systems can evolve towards greater evolvability. Again, note the reappearance of teleological language. Not only can we now understand the workings of ***formal*** cause: decoupled from energetic considerations, formal causes are the operation of second order context-sensitive constraints acting as a process of selection (regulation, modulation).[17] Patterns, which are not other than relations, are far from epiphenomenal; they are indeed causally potent. So top-down causality understood in this manner, I believe, is all one needs to refute supervenience à la Kim. If causally effective, the higher level is real. And not only is it causally powerful; it exercises its top-down causality on *its* terms, that is, according to criteria determined at the higher level. ***Final*** causality is also thus compatible with real, ontological emergence: not only is the telos not pre-established or pre-determined; it is also self-organized and thus radically emergent. As mentioned earlier, formal cause (now reinterpreted as the operations of second-order top-down constraints) selects for inclusion in or deletion from an autocalytic cycle those molecules *that enhance and improve the integrity* or cohesion of the higher level. ***Final*** causes (now reinterpreted as the metastable coherence of the higher level organization) are the self-organized telos in evidence in autopoiesis and other autonomous processes. Spinoza's *conatus* identifies these dynamic vectors.

In summary, a rethinking of ***formal*** and ***final*** cause in accordance with science (Science 2.0, let's call it) becomes possible by rethinking the origin and role of boundary conditions in terms of the operation of second-order constraints. Polanyi describes the mind as dependent on the lower neurophysiological events, but, because it is able to harnesses them in such a way that it is undetermined by them, it is thus "free in its actions" (*KB*, 238). Complex dynamical systems theory is in agreement with this position. Beginning at the level of chemistry, each emergent level of dynamical organization is increasingly *autonomous* insofar as selection is carried out *according to criteria determined at the (next) higher level*. We noted earlier that in autocatalysis, molecule C can be replaced by molecule D in the B-Z reaction because of the latter's improved functionality. It is impossible to overemphasize the importance of this point: the top-down regulation or modulation is carried out according to whether the particular micro-array enhances or detracts from macro-level emergent property—its functionality, in this case. As emergent level is added on top of emergent level, cosmology and evolution show a progression towards increasing autonomy. Complex wholes are consequently able to adapt and evolve. In my language this is so because of the workings of top-down, second order constraints and their selection of particular lower level instantiations "according to criteria established at the higher level." This understanding of formal top-down cause as the operation of second-order context-sensitive constraints circumvents any possible charge of violating laws of conservation of matter and energy. On the other hand, the classical notion of substance, among whose essential traits was independence and self-sufficiency, and whose *internal* primary properties were definitive of their essence, must be discarded. Science 2.0 ontology is at once more complex and interesting once we understand the concept of coherence as the product of interrelationships, interdependence, and integration of constraints—in contrast to those features of independence and isolation so prized by Science 1.0.

The point I've been trying to make here is that the general metaphysical framework inherited from the scientific revolution of the seventeenth century and earlier took the following premises for granted: that there must be as much reality in the cause as in the effect and that nothing can cause itself, that nothing can come from nothing and at best emergence occurs through the interplay of two pre-existing somethings, one working bottom-up, the other—an external agent—working as an efficient cause from the outside in (and so emphatically not top-down from whole to part). Complex dynamical systems theory, in contrast, views the causal power of integral wholes and the environments in which they are embedded quite differently: far from being a passive container space that is shaped and thereby brought into existence thanks to the triggering action of an external efficient cause, the complex recursive dynamics of context-sensitive constraints both create and embed themselves in a strongly emergent phenomenon produced at the same time as ***it*** actively modifies the dynamics of its components. Boundary conditions are thus simultaneously cause and product. Such is the mechanism whereby radical novelty appears in nature.

This is not the end of scientific history, however: other philosophical puzzles concerning boundaries still continue to haunt us, foremost among which are issues pertaining to the identity and individuation of complex systems. But that is a story for another day.

ENDNOTES

[1]Pattern creation is information creation (Brillouin's structure creation as in-formation).

[2]Personal conversation.

[3]Mullins 2013, emphasis mine.

[4]"In so far as a thing is an organic unity, it cannot be acted on by itself; for it is one and not two different things" (*Meta.* IX.I, I O46a28- 30, emphasis mine). See also *Physics* VIII: "It does not move as a whole, and it is not moved as a whole; A moves and only B is moved" (258a22- 27, emphasis mine). The belief that nothing can cause itself can be traced to Aristotle. Despite his views concerning the need for an appeal to the four causes in every acceptable explanation, in *Physics* VIII Aristotle places unmeetable restrictions on any attempt to flesh out the meaning of formal cause because in his concern to establish that the universe does not bring itself into existence—and the way potentiality and actuality function in causality (causes, qua actual, transform the potential into the actual, so the potential, while not yet acted upon, has less actuality)—"nothing can cause itself." For an extensive discussion see Gill & Lennox, 1994.

[5]*Any* cause? Even Aristotle holds this view (see his proofs for a First Mover). The principle goes hand in hand with a metaphysics of substance such that substances are by definition capable of independent existence and are ontologically self-sufficient. Independence, stability, and equilibrium are the hallmarks of Science 1.0. In contrast, interdependence and resilience will become the hallmark of Science 2.0.

[6]How does one entity causally influence the other (without violating the laws of conservation of mass and energy)? Since the foundation of substance metaphysics was held to reside in the essential primary qualities (such as mass) of those atomic entities, relational properties such as temperature and color are held to be subjective and epiphenomenal, summarized in the dismissive term "secondary." Once relations are dismissed, the causal efficacy of interactions is rendered otiose–and there is no way to recover the integrity of organisms or explain how the whole affects the parts. "*Il faut tuer pour analyser*" (Montaigne).

[7]That is even Aristotle's way out. Despite his belief in the reality and efficacy of formal causes, his descriptions of intentional behavior are such that one part of the agent, qua active, causes or changes another part of the agent, qua passive. Because actuality has more reality than potency, this principle is

at work in cosmological proofs of the existence of God throughout history; pure potency on its own is causally impotent. So by claiming that one (qua actual) part of an agent causes another part (qua potential) to become actual, the principle that nothing causes itself is upheld. True emergence is absent in Aristotle; only development is ontologically possible. See note 3 above.

[8]Studying systems as if they were closed was a further assumption that compounded the problem (see Latour and Toulmin, for example).

[9]Note the reappearance of the language of finality.

[10]In the case of dust devils or tornadoes, for example, meteorological conditions establish the boundary conditions within which the dust devil or tornado organizes. The dust devil and tornado have no role in setting or maintaining those meteorological conditions.

[11]I am increasingly drawn to the thesis that although there must initially exist a minimal degree of openness at the lowest level for complexity to self-organize, quantum indeterminacy provides a foundation for this potential. Openness, therefore, doesn't just percolate upwards from quantum indeterminacy, but is expanded by the multiple realizability that hierarchization implies. Once context-sensitive feedback effects closure, the emergence of the type-token distinction and the relative indifference towards their particular instantiation is the hallmark of the evolution of evolvability. That is the progressive evolution of autonomy, so long as the "sloppier" (more abstract, more general) higher level criteria are satisfied.

[12]Clearly top-down causality does not violate energetic considerations.

[13]All languages have a characteristic distribution of letters: a smaller percentage of z's and q's in English, more in Czech.

[14]In English, given t-i-o, n is likely to follow. Context-sensitive constraints are measured by conditional probabilities.

[16]Note my reluctance to use the term "thing." The terms reflect the restructured dynamical relationships among the components of the lower level. See Moreno and Mossio for a thorough analysis of dynamic decoupling. [17]Salthe and Hoffmeyer have analyzed the semiotic aspect of this selection process.

REFERENCES

Agosta, S.J. and J. A. Klemens. 2008. Ecological fitting by phenotypically flexible genotypes: implications for species, associations, community assembly and evolution. *Ecology Letters* 11 (2008): 1123-1134.

Brillouin, L. 1962. *Science and information theory*. 2nd ed. New York: Academic Press.

Brooks, D.R. and S.J. Agresta. 2012. Children of time: The extended synthesis and major metaphors of evolution. *Zoologia* 29, no. 6: 497–514.

Brooks, D.R. and E.O. Wiley. 1988. *Entropy as evolution*. 2nd ed. Chicago: University of Chicago Press.

Cilliers, P. 2002. Why we cannot know complex things completely. *Emergence* 4, no.1-2: 77–84.

Collier, J. and C. Hooker. 1999. Complexly organised dynamical systems. *Open Systems and Information Dynamics* 6: 241-302.

Depew, D. and B. Weber. 1995. *Darwinism evolving.* Cambridge, MA: MIT Press.

Fromm, J. 2005. Types and forms of emergence. http://arxiv.org/ftp/nlin/papers/0506/0506028.pdf

Gatlin, L. 1973. *Information theory and the living system.* New York: Columbia University Press.

Hoffmeyer, J. 2009. *Biosemiotics: An examination into the signs of life and the life of signs*. Scranton, PA: Scranton University Press.

Juarrero, A. 1999. *Dynamics in action: Intentional behavior as a complex system*. Cambridge, MA: MIT Press.

Juarrero-Roque, A. 1985. Kant's concept of teleology and modern chemistry. *Review of Metaphysics* 39: 107- 35.

Kant, I. 1980. The critique of teleological judgement. In *The Critique of Judgement*, trans. J. C. Meredith. Oxford: Oxford University Press.

Latour, B.1993. *We have never been modern.* Cambridge, MA: Harvard University Press.

Moreno, A. 2007. A systemic approach to the origin of biological organization. In *Systems Biology: Philosophical Foundations*. Fred Boogerd, et al., eds. Amsterdam: Elsevier.

_____. and K. Ruiz-Mirazo. 1999. Metabolism and the problem of universalization. *Biosystems* 49: 243-268.

_____. A. and A. Mossio. *Autonomy*. (Springer, forthcoming).

Mossio, M. and A. Moreno. 2010. Organisational closure in biological organisms. *History and Philosophy of the Life Sciences* 32: 269-88.

Mullins, Phil. 2013. Polanyi on the principle of marginal control. Unpublished manuscript.

Polanyi, M. 1958. *Personal knowledge: towards a post-critical philosophy.* Chicago: University of Chicago Press.

_____. 1965. Wesleyan Lectures. http://www.missouriwestern.edu/orgs/polanyi/WesleyanLectures/WesleyanLecturesIntro.htm.

_____. 1966. *The tacit dimension.* Garden City, NY: Doubleday and Company, Inc.

_____. 1969. Life's irreducible structure. In *Knowing and being.* Marjorie Grene, ed. Chicago: University of Chicago Press.

_____. 1997. Life transcending physics and chemistry. In *Society, Economics and Philosophy*. R. T. Allen, ed. New Brunswick, NY: Transaction.

Prigogine, I. 1976. Order through fluctuation: Self-organization and social systems. In *Evolution and consciousness: Human systems in transition*. E. Jantsch and C. Waddington, eds. Reading, MA: Addison-Wesley.

_____. 1996. *The end of certainty: Time, chaos and the new laws of nature*. New York: Free Press.

_____ and G. Nicolis. 1977. *Self-organization in non-equilibrium systems: From dissipative structures to order through fluctuations*. New York: Wiley.

_____ and I. Stengers. 1984. *Order out of chaos: Man's new dialogue with nature*. New York: Bantam.

Salthe, Stanley N. 1985. *Evolving hierarchical systems: Their structure and representation*. New York: Columbia University Press.

Salthe, S. 993. Development and evolution as aspects of self-organization. In *Theory of evolution: In need of a new synthesis*? M . Sintonen and S. Siren, eds. *Philosophical Studies from the University of Tampere* 50: 5-19.

_____. 1993. *Development and evolution*. Cambridge, MA: MIT Press.

Toulmin, S. 1990. *Cosmopolis: The hidden agenda of modernity*. New York: Free Press.

Ulanowicz, R. 1990. Aristotelean causalities in ecosystem development. *Oikos* 57: 42-48.

_____. 1997. *Ecology: The ascendant perspective.* New York: Columbia University Press.