

On the Ordinality of Causes in Complex Autocatalytic Systems

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ABSTRACT: The convention in chemical dynamics usually is to identify the reactant and catalytic molecules as the active agencies that combine in mechanical fashion to constitute a reaction process. When macromolecules grow large and complex enough to exhibit some plasticity, however, the subsequent directions in which these molecules change may be guided more by the nexus of chemical reactions in which they participate. In particular, configurations of autocatalytic reactions among plastic macromolecules can come to exert more agency upon the component reactants and mechanisms than *vice versa*, and the nexus of such processes retains its identity longer than do the latter, more transient participants. Whence, the ascendancy of autocatalytic forms as causal agencies provides a natural example of the phenomenon of “emergence” and affords a way out of the conundrums that currently obfuscate the issue of the origin of life.

KEYWORDS: autocatalysis; causality; centripetality; process philosophy; propensities; selection

Chemistry and physics are often lumped together as exemplars of “hard” science. Chemistry departs from physics, however, in that the structures of interacting entities play a more prominent role in chemical dynamics. With structure also arises the possibility for asymmetry, which is essentially foreign to most laws of physics.¹ Furthermore, as compounds increase in complexity, the combinatorics of chemical structures becomes so immense that one can begin to talk of a virtual continuum of chemical forms. That is, complex chemical forms often can be considered to have malleable structures, and this plasticity becomes most evident in large biomolecules, where chemistry makes contact with biology, and material forms actively begin to evolve. On the matter of evolution, the late Karl Popper believed that science will never achieve an “evolutionary theory of knowledge” until our basic notions of causality have been reformulated.² For chemistry, as for physics, causality has long been identified as either material or mechanical in nature—all other types being strictly

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excluded. This restriction, which dates to the Enlightenment, is at the core of what makes chemistry a “hard” science. One takes on great risk, therefore, by tampering with mechanical closure; but, if Popper is correct, doing so is a prerequisite before one can achieve a clearer picture of the transition from chemistry to biology and endue a rational and natural meaning to the concept of “emergence.”

It is, therefore, with some trepidation (but not without ample precedent) that we now consider the proposition that not all causal agencies derive from enduring physical objects. Specifically, we wish to investigate whether it makes any sense to consider objects and events as being elicited by processes. Such is the thrust of the “process philosophy” of Alfred North Whitehead and Charles Saunders Peirce. There are also strong implications of “process as cause” in the field of network thermodynamics (NT), which treats the relationships between generalized processes (called “through variables”) that are caused (in conventional manner) by corresponding potential gradients (“across variables”). What is different about NT is the “dual theorem” of Bernardus Tellegen, who demonstrated how it is always possible to construct a “dual” representation of an NT problem wherein the through and across variables exchange roles.³ In other words, in the quasi-linear realm of NT, a process is just as likely to elicit an object as an object is to drive a process.

Of course, the domain of chemical reactions is usually non-linear, and it is a bit of a stretch to imagine an object’s being the result of but a single process. What seems more plausible, however, is that an object might result from the conjunction of several processes. Hence, the proposition that we wish to explore here is that the most prominent cause of some objects is the nexus of processes in which they are imbedded. To be more concise about what might constitute an appropriate configuration of processes, we now consider the example of autocatalysis.

Here we define autocatalysis to be a particular manifestation of a positive feedback loop wherein a positive effect is contributed by every link to its downstream neighbor. Without loss of generality, we will confine our discussion to the serial, circular conjunction of three processes (such as reaction rates) A, B, and C. When these processes involve very simple, virtually immutable chemical forms, then the entire system functions in wholly mechanical fashion. Any increase in A will invoke a corresponding increase in B, which in turn elicits an increase in C, and whence back to A.

Matters become quite different, however, as soon as the elements engaged in the processes become combinatorially complex. Such entities, having many nearby, almost identical, forms are capable of small, contingent changes in structure, and will continue to function in the autocatalytic loop as before, albeit with somewhat more or less effectiveness. It would also be more appropriate under such circumstances to say that the action of process A has a *propensity* to augment the second process B. That is, the response of B to A is not prescribed deterministically. Rather, when process A increases in magnitude, most (but not all) of the time B also will increase. B tends to accelerate C in similar fashion, and C has the same effect upon A.

Autocatalysis gives rise to several system attributes, which, as a whole, distinguish the behavior of the system from one that can be decomposed into simple mechanisms.⁴ Most germane is that such autocatalysis now becomes capable of exerting *selection* pressure upon its ever-changing, malleable constituents. To see this, we consider a small spontaneous change in process B. If that change either makes B more sensitive to A or a more effective catalyst of C, then the transition will receive

enhanced stimulus from A. Conversely, if the change in B either makes it less sensitive to the effects of A or a weaker catalyst of C, then that perturbation will likely receive diminished support from A. We note three things about such selection: (1) that it acts on the constituent processes or mechanisms as well as on the elements themselves; (2) that it arises within the system, not external to the system; and (3) that it can act in a positive way to select *for* a particular system result (greater autocatalysis), rather than always *against* the persistence of an individual chemical form. The first attribute defeats attempts at reductionism, whilst the latter two distinguish autocatalytic selection from the “natural selection” of evolutionary theory.

It should be noted in particular that any change in B is likely to involve a change in the amounts of material and energy that are required to sustain process B. Whence, corollary to the selection pressure is the tendency to reward and support those changes that serve to bring ever more resources into B. As this circumstance pertains to any and all members of the feedback loop, any autocatalytic cycle becomes the epicenter of a *centripetal* configuration, towards which as many resources as available will converge. Even in the absence of any spatial integument (as required by the related scenario called autopoiesis⁵), the autocatalytic loop itself defines the focus of flows.

Centripetality implies that whenever two or more autocatalytic loops exist in the same system and draw from the same pool of finite resources, *competition* among the foci will ensue. In particular, whenever two loops share pathway segments in common, the result of this competition is likely to be the exclusion or radical diminution of one of the non-overlapping sections. For example, should a new element D happen to appear and to connect with A and C in parallel to their connections with B, then if D is more sensitive to A and/or a better catalyst of C, the ensuing dynamics should favor D over B to the extent that B will either fade into the background or disappear altogether. That is, the selection pressure and centripetality generated by complex autocatalysis can guide the replacement of elements.

Of course, if B can be replaced by D, there is no reason why C cannot be replaced by E and A by F, so that the cycle A,B,C could eventually transform into D,E,F. This possibility implies that the characteristic lifetime of the autocatalytic cycle generally exceeds those of most of its constituents. The incipience of the autocatalytic form before, and especially its persistence beyond, the lifetimes of most of its constituents imparts causal priority to the agency of the configuration of processes. True, the inception of the feedback loop can be interpreted as the consequence of conventional mechanistic causes. Once in existence and generating its own selection pressures, however, those instigating mechanisms become accidental to the selection agency that arises. Any argument seeking to explain the behavior of the whole system entirely as the result of shorter-lived constituents erroneously ignores the ascendant agency of the configuration of processes, which winnows those ephemeral and transitory mechanisms.

Ever since Democritus, the aim of rational explanation has been to portray all processes as the consequence of universal laws that act on eternal and unchanging fundamental atoms. This reductionist agenda has worked reasonably well at atomic and subatomic scales, but once one encounters macromolecules, durability is reversed. At the mesoscales, it is the configurations of processes that are most enduring—in comparison, their constituents appear merely as transients. The most natural direction for causality to act at intermediate scales is from the persistent configura-

tions of processes towards their transient constituents, whose creation the former mediate.

Those who feel uncomfortable with this reversal of roles might become less anxious once it is explained how the new order obviates some of the most pressing philosophical concerns about the mysteries surrounding “emergence” and the origin of life. It should be recalled that before the Enlightenment life was considered almost universal, so that the greatest philosophical conundrum was how to explain the presence of death in the world.⁶ Upon the rise of materialism more than 300 years ago the perspective was radically reversed. Today all material is presumed dead, and the greatest challenge has become to explain how life appeared on the scene. If, however, one’s perspective were to shift so as to place more emphasis upon processes, both previous viewpoints would appear as unrealistic extremes. Physicists relate how the conjunction of processes that gave rise to the elementary forms of matter as we know them bear marked formal similarity to those involved in the evolution of living systems.⁷ No longer must dead matter and living forms be viewed as separated by an unbridgeable chasm, but rather they both can now be viewed as outgrowths of a common form of creative agency.⁸

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