On causality in non-linear complex systems: the developmentalist perspective

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Science seeks to delineate causal relationships in an effort to explain material phenomena, with the ultimate goal being to understand, and whenever possible predict, events in the natural world. In the biological sciences, and especially biomedical science, causality is typically reduced to those molecular and cellular mechanics that can be isolated in the laboratory and thence manipulated experimentally. However, increasing awareness of emergent phenomena produced by complexity and non-linearity has exposed the limitations of such reductionism. Events in nature are the outcome of processes carried out by complex systems of interactions produced by historical contingency within dissipative structures that are far from thermodynamic equilibrium. As such, they cannot be adequately explained in terms of lower level mechanics that are elucidated under artificial laboratory conditions. Rather, a full causal explanation requires comprehensive examination of the flow networks and hierarchical relationships that define a system and the context within which it exists.

The fact that hierarchical context plays a critical role in determining the outcome of events reinvigorates Aristotelian conceptions of causality. One such perspective, which I refer to as *developmentalism*, views all causal relationships as products of development at some level. Development (also known as 'self-organization') occurs via the selective agency of autocatalytic cycles inherent in certain configurations of processes, which competitively organizes a system as resources become limiting. In this view bottom-up causality (the concern of reductionism) holds sway mainly in immature systems, whereas top-down causality (organizational or informational constraint) dominates mature systems, the functioning of which is less dependent (and more constraining) on the activities of their lower-level parts. Extrapolating the developmentalist perspective to the limit, one might posit that the ultimate arbiters of causality, the 'laws of physics', are themselves no more than organizational constraints produced by (and contingent upon) the early development of the universe. The causal relationships that define chemistry and biology are more highly specified organizational constraints produced by later development. Developmentalism helps resolve a number of long-standing dialectics concerned with causality, including reductionism/wholism, orthogenesis/adaptation, and stasis/change.

In biological sciences, developmentalism engenders a discourse that overcomes barriers imposed by the still-dominant paradigms of molecular reductionism on the one hand and Darwinian evolution on the other. With regard to the former, it provides a better interpretive framework for the new science of 'systems-biology', which seeks to elucidate regulatory networks that control ontogeny, stem cell biology, and the etiology of disease. With regard to the latter, it provides an intelligible bridge between chemistry and biology, and hence an explanation for the natural origin of life. Finally, developmentalism, being an inherently ecological perspective, is well-suited as a paradigm for addressing problems of environmental management and sustainability.