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Stuart A. Kauffman, "A World Beyond Physics: The Emergence and Evolution of Life."

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Stuart A. Kauffman. *A World Beyond Physics: The Emergence and Evolution of Life*. Oxford University Press 2019. 168 pp. $24.95 USD (Hardcover ISBN 9780190871338).

According to veteran biological theorist Stuart Kauffman, the goal of his recent volume, *A World Beyond Physics*, is to show that the 'machine theory of the world' is incorrect, or at least substantially incomplete. Articulated initially by thinkers such as Descartes, Newton, and Laplace, and largely taken for granted within contemporary physical science, the machine theory pictures the world in terms of physical objects interacting according to mathematical laws. Kauffman draws attention to two important features of this theory. On the one hand, the theory entails that all the 'explanatory arrows' in science point downwards, to progressively more minute aspects of physical reality (10). To explain any macroscopic phenomenon means to relate that phenomenon to underlying, micro-physical causes. Second, according to Kauffman, machine theory suggests that future events can be precisely predicted. Given a sufficiently comprehensive knowledge of the position and momenta of particles as well as physical laws—a knowledge of the sort that Laplace bestows on his famous 'demon'—it is possible to determine the position and momentum of any object at any future moment (11).

What is wrong with this picture? According to Kauffman, machine theory cannot fully account for the living world. Suppose for example that we are interested in understanding why animals have hearts. In order to answer this question, Kauffman says, we cannot attend just to the molecular structure of hearts, even if it is true in a narrow sense that hearts result from the activity of molecules. Instead, it is necessary to reverse the explanatory arrows and look *upwards*, toward the biological context within which hearts exist. From that perspective, the basic answer is clear. Hearts exist because they enable the circulation of blood throughout animal bodies; and the efficient circulation of blood promotes the survival of organisms that have hearts (14). Absent this perspective on the heart's *function* relative to the business of survival—a perspective which cannot be articulated within the physicist's conceptual framework—our understanding of the heart remains incomplete.

According to Kaufmann, the living world also mocks the second characteristic pretension of the machine theory. Unlike the movements of particles with a closed physical system, biological evolution cannot be determined in advance. Kauffman draws attention in this context to 'exaptations'. Identified initially by Darwin as 'pre-adaptations' and later renamed by Stephen Jay Gould, an exaptation is a biological trait that has been shaped by natural selection to perform a given function, but which acquires a new and different function within a different environmental context. Thus, feathers originally evolved for thermoregulation but later came to be used in the service of flight (116). Kaufmann's point is that exaptations cannot be predicted in advance. Even if it seems retrospectively clear how and why feathered creatures developed the ability to fly, given the ecological circumstances in which they found themselves, we could not possibly foresee this development.

The issue here is not a lack of information. Even if we found ourselves in a position akin to that of Laplace's demon, knowing the position, habits, and environmental circumstances of every living thing on earth, we would still not be able to foresee the traits and functions that would later emerge. Nor is the problem one of complexity. The factors that made flight adaptive for the flightless ancestors of birds were undoubtedly quite multifarious, involving environmental circumstances and the evolutionary pathways of neighboring species, but complexity alone does not create an *in principle* barrier to prediction. Instead, the problem has to do with the nature of biological functions. Given a closed physical system, Kauffman notes, we can articulate 'all possible positions and momenta' of its constituent elements. For the evolutionary biologist, in contrast, there is no meaningful way of enumerating the *possible* functions of feathers, or any other trait. The list of ways that feathers can be co-opted by natural selection is 'indefinite' (119). What's more, these various possibilities are not ordered in any precise way. While it was certainly more likely that feathers would be co-opted for flight than for digestion, we cannot assign a numerical value to this difference in probability. According to Kauffman, this means that we lack the conceptual tools necessary for prediction. Since we don't know how nature *can* develop, or how intrinsically likely any given development is, we don't know how nature *will* develop.

Beyond thinking through the challenge that living things present for our understanding, Kauffman is also interested in how living things are *possible* in the first place. What makes this question interesting, from his perspective, is that the existence of living things appears to violate a fundamental physical law. Whereas thermodynamics predicts a gradual increase in entropy, or disorder, living things present the spectacle of a constant upsurge in order and complexity (5). According to Kauffman, it has only recently become possible to resolve this contradiction in a satisfactory way, with the theory of 'constraint closure' proposed by Maël Montévil and Matteo Mossio. Montévil and Mossio's theory proposes that living things are unique in the universe for the way in which they harness and sustain energy. In the inorganic world, energy is harnessed through the deliberate construction of 'constraints'. By igniting gunpowder within the barrel of a cannon, we channel the energy released by the gunpowder in a particular direction, preventing it from simply dissipating into the air (24). What is remarkable about the living world is that the role of the 'third party' in the construction of constraints is eliminated. According to Montévil and Mossio, living things construct their *own* constraints. As living things evolve and develop, they create channels through which the energy absorbed from their environments can be efficiently directed. Most significantly, these constraints take the form a loop, such that the energy that is channeled through the constraints is directed toward building the *same* constraints. It is by virtue of this overall form of organization—a form of organization that cannot be 'prestated' on the basis of physical laws—that living things are able to overcome the otherwise inevitable increase in entropy.

Kaufmann's answer to the question of how living things are possible creates an additional challenge in turn. In short, how did living things emerge in the first place? How did inorganic nature give rise to objects that embody 'holistic', or emergent properties not present at the level of inorganic nature itself? Kauffman's reply is that such objects may arise as a relatively straightforward consequence of molecular diversity. Given a 'sufficiently diverse chemical soup,' we can expect to see the emergence of integrated 'sets' of molecules—sets that have achieved a kind of self-sufficiency, or closure, in the sense that all of the molecules in the set are catalyzed by *other molecules* in the set (64).

To be sure, there is a considerable distance between the mathematical possibility of 'autocatalytic' sets and living organisms. On the one hand, it is necessary to show that such sets could have evolved a 'housing' of some kind, such that they do not simply dissolve into the surrounding environment. More importantly, it is necessary to show that such sets can *reproduce*. Evolution in the Darwinian sense can only get underway, Kauffman notes, once relatively 'fit' autocatalytic sets are able to propagate.

For the purposes of *A World Beyond Physics,* Kaufmann does not close this distance in any conclusive way. Given the present state of scientific understanding, the most that he can do is to show that there is *some* story leading from autocatalytic sets to full-fledged living organisms. Fortunately, this does not detract from the main interest of the book, which lies in its exploration of the novel conceptual space that the holistic perspective on organisms makes accessible.

Some of this novel conceptual space has been sketched above. According to Kauffman, consideration of the living world compels us to recognize that the causal-deterministic perspective is not exhaustive. Certain phenomena, biological functions and indeed organisms as a whole, cannot be understood as the inevitable effects of antecedent causes. Toward the end of his book, Kaufmann develops this line of thinking further, looking at the effects that organisms themselves produce. Understanding this, according to Kauffman, requires abandoning the language of causality altogether. Organisms, he thinks, do not *cause* things to happen. Organisms *enable* or *make possible* other events (117). Thus, the hippopotamus does not *cause* the small fish known as the barbel to flourish. The hippopotamus *enables* this species to flourish by providing it with an opportunity to feed, namely, on parasites found on the hippo's skin. The hippopotamus is a 'niche' for the barbel.

This results in a vision of nature that is slightly different than Darwin's. In *On the Origin of Species*, Darwin famously remarked that 'the face of Nature may be compared to a yielding surface, with ten thousand sharp wedges packed close together and driven inwards by incessant blows, sometimes one wedge being struck, and then another with greater force.' As new species emerge, in other words, they compete for space within a tightly packed and competitive arena. For Kauffman, on the other hand, new species do not simply *find a place* within nature. They reshape it. Each new species brings into being new possibilities, new opportunities for other kinds of organisms, including bacteria and viruses, to prosper (106).

In the concluding chapter of his book, Kaufmann notes that the 'biosphere' is analogous to the economy in this respect. New technologies, Kauffman notes, do not simply crowd out previously existing technologies. Instead, new technologies represent opportunities for *additional*, complementary technologies and services (131). Thus, the emergence of the internet did much more than simply replace previously existing modes of communication. It created opportunities for services which have no real analogue within the pre-internet economy, for example, cybersecurity software and consulting. Most importantly for Kauffman, it did so in a way that could not be prestated—meaning that both the biosphere and economy are effectively 'beyond physics'.

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