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Thermodynamics, Information, and Evolution: The Problem of Reductionism

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Few issues have been so actively debated by philosophers of science, and by scientists engaged in philosophical matters, as the relationship between the biological and the physical sciences or between organisms and inorganic matter. The controversy is often referred to as 'the problem of reductionism', but several issues are at stake that are not always adequately distinguished by those engaged in controversy. Issues about the relationship between the biological and the physical sciences fall into at least three domains, which may be called 'ontological', 'methodological', and 'epistemological'.

In the ontological (or 'structural', or 'constitutive') domain, the issue is whether or not physicochemical entities and processes underlie all living phenomena. Are organisms constituted of the same components as those making up inorganic matter? Or do organisms consist of other entities besides atoms and molecules? This is the old question of mechanism versus vitalism, which already engaged Aristotle, was extensively discussed by Thomas Aquinas and the scholastics as well as by the Cartesians, and became the subject of active debate once again since the late nineteenth century with the rise of modern biology.

The mechanist position is that organisms are ultimately made up of the same atoms and subatomic particles that make up inorganic matter. Ontological reductionism is the claim that organisms are exhaustively composed of nonliving parts: no substance or other residue remains after all atoms making up an organism are taken into account. Ontological reductionism also implies that the laws of physics and chemistry fully apply to all biological processes at the level of atoms and molecules. Vitalists argue, on the contrary, that organisms are made up not only of material components (atoms and their aggregations) but also of some nonmaterial entity, variously called entelechy, vital force, radial energy, and the like.

At present, vitalism has few proponents among mainstream biologists or philosophers of science. Biology has been enormously successful in explaining organisms and living processes without recourse to any non-material entities. Moreover, vitalism does not meet the requirements of a scientific hypothesis: it is not subject to the possibility of empirical falsification nor does it lead to fruitful observations and experiments.

Ontological antireductionism, however, has been also propounded in a formulation that does not imply vitalism. The argument is that organisms exhibit 'emergent' properties besides those of their physical components. The functional properties of the human eye, for example, are not attributes that can be predicated of the component atoms in separation.

The question of emergent properties is not exclusive to biology, but applies to all complex structures. For example, does common ethyl alcohol have properties other than those of the component elements carbon, hydrogen, and oxygen? The general formulation of this question is whether the properties of a particular object are simply the properties of its component parts, organized in certain ways. Thus formulated, this may be seen as a spurious question that can be settled by agreement as to what is to be included among the properties of components. If among the properties of carbon, oxygen, and hydrogen we include their association into ethanol and the properties of the latter, then emergent properties do not exist. If we only include the properties they exhibit in isolation, then ethanol has emergent properties.

The definitional strategem to which I have just resorted leads to a resolution of the emergent-properties issue that is not particularly enlightening. It raises the further question of the grounds on which we should decide whether or not to include among the properties of an object those it has when in association with other objects. I believe there is a sensible way of deciding this issue, namely by reference to our ability for ascertaining the properties of an object when it is studied in isolation. Can the properties of ethanol be *inferred* from the study of carbon, oxygen, and hydrogen? Those properties of ethanol that cannot be ascertained by studying separately the three component elements would not be listed among the properties of carbon, oxygen, or hydrogen. Notice, however, that in proposing this criterion for deciding whether or not emergent properties exist, I have shifted the issue from the ontological to the epistemological domain. The question now is whether the laws and theories accounting for the behavior of complex systems can be derived from the laws and theories developed for the study of their components. I will consider epistemological reductionism in a moment, but I must first turn to the issue of methodological reductionism.

There are reductionist questions that might be called methodological (or 'procedural', or 'strategical'), which concern the strategy of research and the acquisition of knowledge, the approaches followed in the investigation of living beings. Reductionism in this case refers to the claim that biological problems should be investigated by studying the underlying (ultimately, physicochemical) processes. Genetics, for example, should seek to understand heredity in terms of the structure and properties of DNA, RNA, enzymes, and other macromolecules, rather than in terms of whole organisms – the level at which the Mendelian laws of inheritance are formulated. Research at other levels, it might be argued, is not worth pursuing since biological phenomena can be fully understood only at the molecular and atomic levels.

Questions of research strategy are of intense concern to practicing scientists since they implicate matters of academic turf and decisions about research support. The enormous success of the analytical method in science is apparent to most observers. It is also apparent that the understanding of living processes at any level of organization is much advanced by knowledge of the underlying processes. But only the most unthoughtful are likely to propose that reductionist methodologies should prevail to the exclusion of all investigations at the level of whole organisms. This would imply the unreasonable claim that genetic investigations should not have been undertaken until the discovery of DNA as the hereditary material, or that a moratorium should be declared in ecology until we can investigate the physicochemical processes underlying ecological interactions.

The only criterion of validity for a research strategy is its success. Synthetic as well as analytic methods of investigation are justified if they further our understanding of a phenomenon, if they increase knowledge. Reductionist and nonreductionist ('compositionist' or 'holist') approaches to the study of biological problems are complementary.

The third kind of reductionist issue concerns problems that are epistemological (or 'theoretical', or 'explanatory'). The central question is whether the theories and laws of biology can be derived from the laws and theories of physics and chemistry. If so, biology would not be a separate discipline, but simply a special case of physics or chemistry. Epistemological issues are of great interest to philosophers of science. They are, indeed, of great relevance for uncovering the nature and progress of science.

Science seeks to discover patterns of relations among diverse sorts of phenomena in such a way that a few principles can explain a large number of propositions concerning those phenomena. Scientific knowledge increments in multifarious ways. Particularly productive is the development of gradually more comprehensive theories, when it can be shown that theories and laws that seemed unrelated are integrated in a single theory of great generality. In some instances, theories became integrated because the theories and discoveries of a branch of science are shown to be special cases of the theoretical constructs from another branch of science. In such case, the former discipline is 'reduced' to the latter one. Epistemological reduction simplifies science and extends the explanatory power of scientific principles, which conforms to the goals of science. A standard example is the reduction of thermodynamics to statistical mechanics made possible by the discovery that the temperature of a gas reflects the mean kinetic energy of its molecules. Another example is the reduction of a large sector of chemistry to physics after it was shown that the valence of an element bears a simple relation to the number of electrons in the outer orbit of an atom.

In biology, many genetic concepts and theories have been reduced to chemistry with the discovery of the structure and mode of replication and action of the DNA, the hereditary material. In spite of this and other impressive advances of molecular biology, such as in the understanding of nerve impulses or in the reconstruction of evolutionary history, it would seem that the epistemological reduction of biology to the physical sciences is not possible at present nor is likely to be effected in the foreseeable future. Some biological disciplines, such as ecology, sociobiology, systematics, biogeography, and others, study organisms or their assemblages at levels of organization far removed from the physicochemical. Notions from the physical sciences would seem wondrously insufficient to understand, for example, the geographic patterns of species distributions, or the cast organization of social insects.

This view has now been challenged by J.S. Wicken in an ambitious book that purports to advance a new evolutionary theory that encompasses prebiotic as well as organismal evolution, grounded as it is on thermodynamic principles. It is Wicken's thesis '(a) that the emergence and evolution of life are phenomena causally connected with the Second Law; and (b) that thermodynamics allows for the understanding of organic nature from organisms to ecosystems' (p. 5). The claims are sweeping: 'By maintaining the part-whole relationality of ecosystem dynamics, thermodynamics addresses these problems by *extending* Darwinian tenets through prebiotic evolution and into life's first murmurings' (p. 120, his italics). '[T]his book aims at joining a century of Darwinian thought with a century of thermodynamic thought ... [I]t attempts to provide *unifying* principles for evolution – from the prebiotic generation of molecular complexity through the self-organization of living systems through their phylogenetic diversification' (p. 9, his italics).

For Wicken, the claim that biology is an autonomous discipline is a 'most unproductive attitude' (p. 55; see p. 120) and indeed the nemesis of biology, particularly evolutionary studies. 'Evolutionary theory has ...

grown up as an "autonomous" science, unconnected with either origins or physical dynamics. Sometimes, this sad truth is voiced in triumphant tones, as in Mayr's ... proclamation that "the past twenty-five years has also seen the final emancipation of biology from the physical sciences" ... Evolution is a science of *connection*, not separation' (p. 55).

If you wonder what in the world may be meant by the last sentence just quoted, you may as well be told that Wicken's book abounds in such vague language as well as in logical fallacies, inconsistencies, and equivocal terminology. Moreover, poetic language and metaphor are hopelessly weaved into the fabric of the argument. Consider, by way of relevant example, the issue of reductionism. Wicken states: 'I am therefore an ontological antireductionist and a methodological reductionist' (p. 11). This statement would seem surprising in view of what I have written above. Hence, one might think that this is a matter of semantics: he is simply using the terms 'ontological' and 'methodological' in some idiosyncratic way. The statement just quoted is immediately followed by this: 'That living systems operate, and came into being, according to materialistic principles does not imply that all those principles can be discovered at any given level of complexity' (p. 11). The initial clause of this sentence would seem a statement of ontological reductionism; the main clause an affirmation of methodological antireductionism, since it refers to the 'discovery' of principles. In the next paragraph, he concludes: 'Thus [the] rejection of ontological reductionism. Organization provides boundary conditions on the operation of physicochemical processes that *cannot be deduced* from the principles governing those processes' (p. 11, my italics). This last sentence would seem to refer to *epistemological* reductionism. Elsewhere on the same page, he writes: 'Life can't, however, be reduced to thermodynamics, or to any combination of physical sciences' (p. 11). We are in a hopeless muddle. Does he now mean that 'biology' cannot be reduced to the physical sciences? Or that 'life' consists of more than just physical components and processes? The next sentence introduces additional confusion: 'What makes the biotic realm unique is that the beings that inhabit it have "sensitivity". They carry subjective maps to which sensations can be referred, and their adaptive maneuverings are predicated on utilizing these maps in interpreting environments' (p. 11). What is the meaning of organisms 'utilizing [subjective] maps in interpreting environments'? And if living beings are characterized by 'sensitivity' and by 'sensations', are not plants living?

I must apologize for abusing the indulgence of the reader in the exegetical exercise of the previous paragraph. But I could see no less onerous way of conveying the tone of Wicken's book: it is a reviewer's obligation to expose opacity and inconsistency, lest they be mistaken for profoundity or insight. Other philosophical issues raised in the book, such as the notions of progress and of teleology, do not fare any better.

Wicken sees the Second Law of thermodynamics as the unifying notion that explains how organisms came about and their evolution. 'Thermodynamic principles operate at different levels of the organic hierarchy ... [L]ife is both operationally and functionally related to the rest of nature, and must be understood in terms of this relationality' (p. 9). Organisms are best defined as 'autocatalytic organizations' (p. 17). Indeed, 'A living system is an example of a "dissipative structure" – a system that maintains a high degree of internal order by dissipating entropy to its surroundings' (p. 31). I have no quarrel with these notions, but they do not say much about organisms and their assemblages in populations, communities, and ecosystems. Thermodynamics has a role to play in the explanation of the function and evolution of organisms, but it is not enough. Thermodynamic principles may be in some biological disciplines necessary, but they are not sufficient.