HTS Teologiese Studies/Theological Studies
ISSN: (Online) 2072-8050, (Print) 0259-9422

Reductionism or holism? The two faces of biology

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Dates:
Received: 27 Nov. 2022
Accepted: 24 Jan. 2023
Published: 08 Mar. 2023

How to cite this article:
Walker, J.A. & Cloete, T.E., 2023, 'Reductionism or holism? The two faces of biology', *HTS Teologiese Studies/Theological Studies* 79(1), a8336. https://doi.org/10.4102/hts.v79i1.8336

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Reductionism and holism, that is, antireductionism, are two of the prevailing paradigms within the philosophy of biology. Reductionists strive to understand biological phenomena by reducing them to a series of levels of complexity with each lower level forming the foundation for the subsequent level, by mapping such biological phenomena inasmuch as possible to the principal phenomena within the fundamental sciences of chemistry and physics. In this way, complex phenomena can be reduced to assemblages of more elementary explananda. Holism, in counterpart, claims that there independently exist phenomena arising from ordered levels of complexity that have intrinsic causal power and cannot be reduced in this way. When dealing with the nature of biology and its unique foundations of essentialism, determinism and ethics, the pedagogical lens through which these foundations are conveyed to learners could provide a limited perspective if only the reductive approach is followed as it would not sensitise learners to the true complexity of the phenomenon of life and the study thereof, and it is the purpose of this article to frame the reductionist–antireductionist debate in order to illustrate this.

Contribution: This article contributes new knowledge to the field of the philosophy of science; more specifically, the philosophy of biology by critically evaluating the pervasive dialectic between the theoretical frameworks of reductionism and antireductionism and alluding to the pedagogical consequences thereof.

Keywords: reductionism; holism; antireductionism; determinism; essentialism; biology.

Introduction: The nature of biology

Biology is generally understood as the scientific study of life. As such, a critical facet of the discipline is that it is continuously pursuing the definition of what is meant by 'life'. The disciplines of biology and philosophy have consequently intersected to adopt heterogeneous descriptions of the nature of life, approached from different perspectives, of which three were posited by Knuuttila and Loettgers (2017) as being of primary significance, namely the theoretical, transdisciplinary and diagnostic approaches.

The theoretical approach synthesises its definitions through the cohesion of theoretical concepts and experimental results as aligned with central focal concepts from various disciplines. Theoretical definitions thus enmesh theoretical principles and experimental results although in each instance the goal is to argue for a particular theoretical perspective. The transdisciplinary approach to defining life also integrates multiple interdisciplinary definitions although it concedes to the transtheoretical heterogeneity present and offers a means of communication within the highly multidisciplinary research communities involved in biology. The diagnostic approach is limited to providing definitions of life that are exclusively indirectly observable and thus provides diagnostic tools to biologists searching for life on other planets, which is generally limited to astrobiology.

Having touched on the multitudinous conceptions of the nature of life, we move on to briefly discuss what is meant by biology as a unique discipline in its pursuit of the study of life. Kloser (2012) posited that with such a diverse body of knowledge concerning the very definition of life, the definition of biology as the study thereof consequentially poses unique philosophical, methodological and ethical challenges and a consensus definition is therefore not feasible and is dependent on the particular field of biological study. Kloser further proposed that despite this limitation, the unique nature of biology can, however, be discerned by three philosophical constructs discerning the nature of biology from the general nature of scientific enquiry: essentialism, determinism and ethics.

Before delving further into these central tenets by which the nature of biology is discerned, it is necessary to discuss that under which it is often subsumed within the educational context – the broader ambit of the nature of science. Science can be broadly defined as the acquisition of knowledge through enquiry (Ramnairin & Padayachee 2015), and the nature of science thus integrates conceptually related educational themes that encompass, *inter alia*, the following: science as a body of knowledge, the nature of science as an investigative endeavour, science as a mode of thought and the intersection of technology, science and society (Chiappetta, Fillman & Sethna 1991). As previously stated, although the nature of biology does fall within the ambit of the nature of science as alluded to herein, it espouses central tenets that point towards its unique nature; we will now thus consider essentialism, determinism and ethics individually as they shape the nature of biology.

Devitt (2018) described essentialism as the philosophical tenet that an organism is defined by its lineage and possesses specific traits that both classify and constitute membership within a specific taxonomic species. Therefore, essentialism is considered a core philosophical construct to the biological classification of organisms. Devitt further observed that essentialism is often challenged by evolution, that is the various interpretations of the Darwinian theory of natural selection and that a consequently significant issue within modern biology is the resultant controversy that exists surrounding the definition and understanding of what constitutes a 'species' and how organisms should be classified in the light of their genetic and morphological diversity.

Next, we move on to discuss determinism in the context of the nature of biology. According to Fleming (2017), determinism is 'the idea whereby any phenomenon in nature is completely determined by pre-existing causes to which it bound by a relationship of necessity and that only one possible future exists'. This leads to causal relationships often being interpreted as 'natural laws', and the shortcomings of this approach are becoming increasingly apparent as modern biology seeks systems-level answers, as will be discussed later when dealing with reductionism. Finally, consideration should be made of the unique ethical landscape presented by biology that includes controversial topics such as embryonic stem cell life sciences research (Kloser 2012), with far-reaching sociocultural consequences and implications.

Reductionism and the 'emergence' of holism

Having discussed what is meant by life, and the unique nature of biology as a discipline concerned with the study of life, we can examine a pervasive dialectic within modern biology and modern biology education: reductionism versus holism or antireductionism. Historically, this dialectic has gained increasing prominence because the landmark discovery of the double-helix structure of DNA in 1953, which gave rise to the field of molecular biology that studies life at the molecular level (Kesić 2016; Mazzocchi 2012; Vance 1996). Reductionism, as described by Allen (1991), may be fundamentally understood as the position that one complete set of entities can be fully explained with reference to another. Allen posited that reductionism essentially espouses a stratified conception of the universe, which claims to facilitate the elimination of the higher levels by completely explaining them using the properties of the lower levels. Allen also noted that reductionist methodological study in the discipline of molecular biology has been philosophically and historically rooted in determinism.

Andersen (2001), while briefly overviewing the history of reductionism, recounted that an important endeavour of much of modern science has been dedicated to the reductionist enterprise of attempts at replacing scientific entities, concepts and relations from one discipline with those of another: this was the case for the mechanical philosophers of the 1600s that attempted to model a plethora of physical phenomena, *inter alia* optics, in terms of models from mechanical theory. Similarly, 19th-century physicists derived the thermodynamic gas laws from observations of patterns in the mechanical behaviour of the gases they studied in terms of their constituent molecules. Andersen also noticed that reductionism further conceptually embodies the explanation of phenomena pertaining to the properties of aggregates, as explained by the constitutive components from which aggregates are formed. Andersen further posited that the ultimate embodiment of the reductionist perspective therefore envisions the world as a series of levels of reduction of increasing complexity, from the scale of elementary subatomic particles through to living organisms and social groups, for which it is expected that each hierarchical level is governed by laws that can be reduced to those of the subordinate level in a sub-type of reduction termed micro-reduction.

The concept of unity of science, advanced by the logical positivists of the early to mid-20th century, such as Oppenheim and Putnam (1958), in their article 'Unity of Science as a Working Hypothesis', emphasised both the transitive and cumulative nature of micro-reductions with the ideal of achieving the complete reduction of science to a single discipline – although the authors neither claim that this hypothesis was necessarily true nor deny that successful unification of science may ultimately be elusive.

Earlier authors during the previous century had rejected the notion of reductionism: John Mill (1843), a British philosopher during the mid-19th century, argued that the properties of constituent elements would not form a basis upon which to derive the properties of molecules and also denied that the components of a living body would provide a concrete basis from which to derive the properties of life. Mid-19th century, George Lewes (1874), another British philosopher, coined the term 'emergence' to describe any observed effect that, although resulting from the components of a system, could not be reduced to the sum of the system's components. He also observed that whether or not an effect can be termed emergent depends on current theories at the time at which the effect is observed; the effect would be termed emergent until such time as its underlying processes could be fully explained.

The standard model of reduction, which forms the basis of most contemporary discussions of reductionism, was proposed by the logical positivist (or rather, logical empiricist) Ernest Nagel in his 1949 essay *The Meaning of Reduction in the Natural Sciences* and subsequently expounded upon in his 1961 book *The Structure of Science*. According to this model, reduction is [...] the explanation of a theory or set of experimental laws established in one area of inquiry, by a theory usually though not invariably formulated for some other domain [...]. In this context, the term 'explanation' refers to that of the deductive-nomological model espoused by logical empiricists: according to this model, explanation refers to the logical deduction of the explanandum (i.e. that which is to be explained) from a set of generalisations containing the laws of nature as well as initial conditional statements.

The limitations of reductionism in the face of modern biological holism

According to the standard model of reduction, it is, however, impossible for the laws of the secondary theory to be derived from those of the primary theory through logic and initial conditions in instances in which terms that are absent from the primary theory are present in the secondary theory. Thus, Nagel introduced two conditions that had to be met in such cases: Firstly, for each term occurring in the secondary scientific discipline that is absent from the primary scientific discipline, assumptions must be introduced linking the relevant term to terms from the primary scientific discipline. This is termed the 'condition of connectability'. Secondly, assuming the aforementioned, the laws of the primary science should allow for the laws of the secondary science to be logically derived. This is termed the 'condition of derivability'. Nagel's model has been prominently criticised by Hull (1974) and Rosenberg (1985) in that formulating a practically enforceable set of relations between the terms describing the two theories may not be feasible. Feyerabend (1962) also earlier criticised the model on the basis that the two theories may be logically incongruent and therefore derivation of one from the other would not be tenable.

Reductive approaches, particularly 'molecular reductionism', focussing on the molecular biological properties of cells, were initially successful in elucidating fundamental concepts of biological cellular function within a deterministic paradigm (Mazzocchi 2012) and yielded the central dogmatic principles of molecular biology (Fleming 2017). However, it is often the case that the reductionist approach is characterised by a concomitant deterministic perspective that conflates determinism with predictability – this consequently provides inaccurate scientific representations of complex systems-level biological phenomena and ignores epistemic limitations with regard to higher levels of ordered complexity (Fleming 2017). As Fleming (2017) noticed, once the dogma of determinism has been set aside, reductionism is a useful tool to facilitate the exploration of phenomena associated with stochastic probability, such as those examined by the field of genetics.

Biology has, however, advanced to the point that the limitations of the molecular-reductionist approach – and by extension the core deterministic dogmas of molecular biology – are becoming increasingly apparent (Green & Batterman 2017) as biology is increasingly concerned with the elucidation of the mechanisms by which the complexities of molecular biochemical pathways and networks support structure and function on a biological level. Techno-scientific advancement has thus given rise to the nascent discipline of systems biology, which attempts – through powerful computational modelling – to elucidate the cohesive nature of the molecular machinery of living organisms (Bizarri, Palombo & Cucina 2013) as the boundaries between medicine and biology have blurred and intersected (Meunier & Nickelsen 2018).

Integrative studies of this kind fall within the realm of antireductionism, or holism, posing a counterpoint to the reductionist perspective. The term 'holism' was originated by the South African politician Jan Smuts (1926) in an attempt to argue against reductionism without resorting to the introduction of abstract metaphysical notions of immaterial substances and their interaction with the material world, as the vitalists had done before him in the preceding centuries. He argued, in essence, that a complex whole supersedes the sum of its parts and that the assemblage of the parts itself has a unique teleological role.

Therefore, antireductionism encompasses the epistemological concept of emergence, as previously alluded to, that constitutes the observation that emergent systems-level properties exist that only come into being with the level of ordered complexity found within living systems (Pigliucchi 2014) and systems biology has allowed for the practical realisation of the 'emergentist' perspective. Emergentism eschews metaphysical ontological notions of the origins of unique properties of biological systems arising at higher levels of systemic organisation while positing the physical existence of such novel properties, each with their own causal power, that can neither be predicted nor be explained through a reduction in terms of either properties or relationships of lower organisational levels (Mazzocchi 2012). Thus, emergentism is an antireductionist paradigm that advocates the concept of downward causation. Downward causation encompasses higher-level functions existing not merely as epiphenomenally cumulative outcomes – as outcomes without intrinsic causal power and merely resulting from lower-level functions – but indeed as outcomes truly arising as causally independent of such lower-level functions (Baetu 2012).

Reductionism versus holism: A closer look

We now examine reductionism and antireductionism in greater detail, within the context of the modern philosophical dialectic. Allen (1991), as an outspoken antireductionist within the field of education, discussed the three different types of reductionism: methodological, epistemological and ontological, as originally espoused by the renowned geneticist and evolutionary biologist Francis Ayala (Ayala 1974). According to Allen, methodological reductionism deconstructs whole entities, which are presently unintelligible, into manageable component parts, identifying their functions and structures, and thus reconstitutes an understanding of their wholes. Allen stated this as an acceptable form of reductionism provided that it is seen as a temporary practice with the aim of reintegrating the individual components into a reconstituted whole, that is contribute towards a holistic understanding. This perspective does not detract from the phenomenon of emergence as pertaining to systems-level complexity. Allen further noticed that it is important, however, to distinguish this view from the perspective of deterministic predictability stating that the reconstituted whole is exclusively an ensemble of individual components, that is the ontological assumption that whole entities are merely comprised by the sum of their individually separable components, which does negate emergence of unique properties at higher levels of ordered complexity.

Epistemological reductionism premises that [...] the conceptions, theories and laws of one branch of science can account for and explain, without remainder, all the phenomena and processes studied by another [...] (Allen 1991). It is an ontological assumption that bases the relevance of biology as solely dependent on the relevance of chemistry and ultimately physics – as was the case wherein the logical positivists of the early to mid-20th century pursued the ultimately unsuccessful project of the unification of science by its reduction to physics (Andersen 2001; Faye 2014).

Depending on the context of the biological topic of discussion, it is often the case that both methodological and epistemological reductionism pre-suppose ontological reductionism (Allen 1991). Ontological reductionism is often equated with physicalism (Rosenberg & Kaplan 2005), that is the doctrine that reality is limited to the observable physical world, from a materialistic monist perspective that assumes that only the physical world exists (Kesić 2016). It considers whether entities existing within one domain comprised the entities of another (Andersen 2001), positing that reality is layered and that each level of reality is nothing but a lower form of another, and that all events and processes of the higher level can be accounted for by reference to those of the lower levels. In this manner, the complexity of nature is reduced to the interactions of simpler constituent structures of matter and phenomena occurring at higher levels are merely regarded as epiphenomenal (Mazzocchi 2012).

Lastly, mention should be made of successive reduction (alternatively termed diachronic, homogenous or domain-preserving reduction) and interlevel reduction (alternatively termed synchronic, heterogeneous or domain-combining reduction) and the distinction between them (Andersen 2001): successive reduction describes, at its core, the succession of theories developed to address the same scientific domain, for example, relativity theory versus classical mechanics. Inter-level reduction, however, describes a reductive relationship between theories addressing domains of objects existing at differing levels of complexity, for example biological organisms versus molecules.

Having addressed reductionism in depth we can now return its counterpart, antireductionism and move on to discuss the various manifestations thereof. Within the biological and scientific communities at large, there has been considerable antireductionist thinking that has formalised two schools of thought, namely epistemological antireductionism and ontological antireductionism (Gatherer 2010). Gatherer has described epistemological antireductionism as [...] the recognition that some phenomena are too complex to be comprehended by human, or even computer, intelligence [...]. He showed that in the biological instance, by extrapolating modern computational power to its theoretical limits, detailed technical arguments could be made that simulations involving genes, and their functions would exceed the theoretical limit that computational power could muster. Extending the description of epistemological antireductionism logically describes ontological antireductionism, according to Gatherer, as [...] the argument that there are certain things, entities or laws, that reductionism can never capture, even if we transcended the epistemological limitations [...].

Gatherer further posited that ontological antireductionism can be subdivided into two kinds, providing different reasons for the posited failure of reductive thinking to capture innate higher-level complexity: constitutive ontological antireductionism and explanatory ontological antireductionism. Constitutive ontological antireductionism deals with metaphysical descriptions of reality, which cannot be studied scientifically, and can be discarded in the context of biology. Explanatory ontological reductionism, in contrast, posits that although a reductionist analysis of a complex system may capture all of its fundamental elements, there would always co-exist emergent properties of a system that are non-reducible, for which it would not be the case that investigators would have merely failed to conceptually reduce them based on the extent of modern knowledge:

For any given higher-level 'macro-state', the possibility exists of numerous lower-level 'micro-states' that could interact and be equally responsible for the observation. Collier (1988) first explored this theme and originally termed this phenomenon 'cohesion' and Gatherer claimed that under such circumstances reduction may be both misleading and pointless. Care should thus be taken when exercising reductive methodology, so as to not subsume one's perspective beneath an ontologically reductive penumbra.

Apart from the methodological, epistemological and ontological classifications, both reductionism and antireductionism have also been classified in terms of 'strength' by Vance (1996), expounding upon classifications that were originally posited by Kitchener (1984), into a taxonomy of reductionist and antireductionist positions that specifically pertain to biology:

- Strong (eliminativist) reductionism claims that biological levels of explanation exist that are independent but not autonomous, with the exception of molecular biology and physics. In this mode, physics or molecular biology will always supersede theoretical biological explanations, that is a symmetrical relationship holds between the reduced and reducing levels
- Weak reductionism claims autonomous levels of theoretical biological explanation with an asymmetrical relationship between levels of explanation, such that the reducing level is preferential to the reduced level
- Strong antireductionism also claims autonomous levels of theoretical biological explanation although, in contrast to weak reductionism, espousing a *symmetrical* relationship between explanatory levels in that no fundamental explanatory level exists
- Weak antireductionism claims – in contrast to strong reductionism – that there do exist autonomous levels of theoretical biological explanation, which express an asymmetrical relationship.

Vance posited that an obvious result of this taxonomy is that weak antireductionism and weak reductionism are equivalent, which is not surprising as the two positions attempt to seek out middle ground. A third and ultimate antireductionist position also exists, namely Heroic antireductionism: this posits that independent levels of explanation do not exist and that putative reducing and reduced theories should be considered complementary elements of a unified whole.

As already alluded to herein, modern biology has advanced to the point where attempts are made to model living systems experimentally within the transdisciplinary field of systems biology (Verhoef et al. 2018). 'Systems-level thinking' (a holistic approach) has consequently encompassed the integrative way of thinking that explains, understands and interprets the complexity of biological systems with reference to wholes that are more complex than the sum of their parts. Thus, systems biology facilitates a heroic methodological antireductionist stance, as it entails the elucidation of complex relationships from vast swathes of data. This coincides with the rhetoric of Kesić (2016), which argued that heroic antireductionism was wrongly subsumed within the realm of epistemological antireductionism, as it is based on a methodological approach that had not yet been developed, owing to techno-scientific computational limitations at the time when Vance (1996) presented his taxonomic classification of antireductionism. Therefore, systems biology provides the hierarchical framework for the modern antireductionist, which descends from heroic methodological antireductionism, through the level of epistemological antireductionism, to finally encompassing ontological antireductionism – a position that defends the independence of biology from physics.

However, should an antireductionist embrace the ontological perspective, this would negate physicalism – an uncomfortable position for biologists as scientists. Therefore, in order for antireductionism to be scientifically defensible in the light of biology, it is necessary to provide a physicalist account of the central theory of biology, namely the principle of natural selection at the core of evolution. Rosenberg and Kaplan (2005) provided a detailed logical analysis that positions the principle of natural selection as an underived law of natural science, in particular a law of chemistry; specifically, the principle of natural selection for molecules. This allows for the reconciliation of physicalism and antireductionism as biology would not be reducible, according to Nagel's standard model of reduction, to physics because the principle of natural selection for molecules would be fundamental and therefore irreducible.

Objections against emergence and the holist perspective

Having traced the origins as well as having dealt with the various taxonomic, hierarchical and etymological interpretations of reductionism and antireductionism, we can now once more turn our attention to emergence, in particular, objections against emergentism. Baetu (2012) posited that although emergent properties in biology do exist, such properties are not best understood from perspective of the explananda concerning higher-level entities. He primarily objected to the ambiguity within the term 'molecular level', as this could relate to several classes of biochemical entity that operates within a particular functional domain. Other objections included the conflation of explanation and prediction, as well as of higher-level 'entities' with higher-level 'wholes', wherein each may either be constituted by the other or embody both classifications: as an example, organisms, cells and cellular organelles could be deemed higher-level 'entities' and their macromolecular constituents such as polymers and molecular mechanisms deemed higher-level 'wholes', but in other instances, a subject may be construed as both whole and entity (such as populations in ecology being at once entities to be studied and wholes composed of individual organisms). Furthermore, he objected to the failure of emergentism to account for mechanistic explanations that, although involving wholes, do not take into account higher-level entities – such as the instance of molecular mechanisms, being wholes not corresponding to specific entities. Finally, he raised the objection that emergentism fails to appreciate the significance of the fundamental molecular context of functional descriptions.

As alluded to here while discussing the conceptual synergy between weak antireductionism and weak reductionism, even systems biology faces challenges with satisfactorily navigating the territory between reductionism and antireductionism, particularly in light of the objections against emergentism: this gives rise to the recently proposed 'organismic theory' of systems biology, as discussed by Rosslenbroich (2017), which attempts to supersede the reductionism versus antireductionism philosophical dialectic. Organicism, as defined by Rosslenbroich, is [...] the point of view that living organisms are complex, hierarchically structured systems, whose parts are all functionally integrated into and coordinated by the system [...]. It perceives nature and living organisms as discrete entities and sub-entities within a massive, cohesive continuum that affect each other within a dynamic matrix of interrelatedness. It thus facilitates the emergence of higher-level properties without constricting their emergence solely to a function of lower-level processes.

Conclusion

Contemporary biologists increasingly encounter the phenomenon of 'epistemic competition' between the opposing philosophical paradigms within the reductionist–antireductionist debate (Gross, Kranke & Meunier 2019). It is only within the spirit of this continued philosophical dialectic that both praxis and poiesis of biology and more broadly Life Sciences can advance. High-school learners' pedagogical experiences, particularly those experiences espousing the unique characteristics of biology as a discipline with reference to the nature of life, would fundamentally shape the conceptual frameworks adopted by learners upon which they would base their future praxes as practicing scientists. This could either empower or disempower them from meaningfully advancing biological study, and it is thus critical that high-school learners understand the unique nature of biological enquiry as pertaining to the ordered complexity of life that it examines, which necessitates a balance between the reductionist and antireductionist perspectives in pedagogical praxis. Understanding the nature of biology thus presents unique philosophical challenges that in turn potentially warrant learners' exposure to holistic epistemological consideration and pedagogical approaches. Furthermore, a focus on the unique nature of biology in pedagogical praxis would guide learners' future approaches to the discipline as practicing biologists.

Acknowledgements

Competing interests

The authors have declared that no competing interest exists.

Authors' contributions

J.A.W. conceptualised and drafted the initial manuscript under the guidance of T.E.C.

Ethical considerations

This article followed all ethical standards for research without direct contact with human or animal subjects.

Funding information

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Data availability

There are no restrictions on data availability concerning this manuscript.

Disclaimer

The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of any affiliated agency of the authors.

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