

Reduction: A Philosophical Analysis

Sahotra Sarkar, *University of Texas at Austin, Texas, USA*

The molecularization of biology has led to a renewed interest in the possibility of reducing biological phenomena to physical interactions.

Introduction

The mechanical philosophy of the seventeenth century, associated with figures such as Descartes, Boyle and Huygens, initiated a pattern of explanation that has persisted in many sciences into the twenty-first century. The mechanical philosophy sought to explain all physical and biological phenomena on the basis of contact interactions between impenetrable particles of matter of which all systems are composed. In the life sciences this led to the conceptualization of living organisms as machines; the most significant result that emerged from this point of view was Harvey's model of the circulatory system. Two assumptions are implicit in the pursuit of mechanical explanations: (1) that phenomena in one domain can be explained on the basis of principles from another domain; and (2) the system to be explained is viewed hierarchically with phenomena at one level being explained from principles operative at lower levels of organization. The philosophical term 'reduction' refers primarily to a type of explanation that is directly descended from these mechanical explanations.

The mechanical philosophy ultimately proved inadequate as a foundation for physical theory. Primarily this happened because of Newton's law of gravitation which, by unifying celestial mechanics with terrestrial mechanics, remained a paradigm for natural law until the twentieth century. By insisting on contact interactions, the mechanical philosophy denied the possibility of action at a distance, which is incorporated in the Newtonian gravitational interaction. In the nineteenth century Helmholtz attempted to relax the mechanical philosophy to allow for all central forces, including gravitation. Even this could not save the mechanical philosophy because some electromagnetic phenomena proved to be recalcitrant.

Meanwhile, Helmholtz and many others also attempted to ground 'biology' (a term that only goes back to 1900) on mechanistic explanations alone, by which they meant purely physicochemical explanation. This programme became central to biology after Lamarck and others insisted on a purely materialistic interpretation of living organisms. What is called 'reductionism' today – and the

term will be defined more precisely below – is the direct descendant of this programme. The main impetus for endorsing reductionism in biology has come from the spectacular successes of molecular biology during the last fifty years (see below).

Discussions of reductionism involve both ontological and epistemological questions, which should be kept distinct. The former include questions about what exists in a system, whether the laws and mechanisms at one level determine phenomena at another, etc. The latter include the questions about whether reductionist explanations of phenomena can be offered and whether research programmes should be based on reductionist strategies. Even if one is an ontological reductionist, it is possible to deny epistemological reductionism, e.g. if attempts at reductionist explanation of some phenomenon continue to fail. Such failures can arise because successful explanation depends on the questions asked and what is known. For instance, a system may be too complex for a reductionist answer to be given for some question asked about it because of the current limitations of computational ability. In biology this is often the case: at present it would be foolhardy to suggest that all organismal behaviour – let alone behaviour at higher ecological levels of organization – can be given reductionist explanations in terms of molecular interactions. Nevertheless, it is probably true that these interactions determine the phenomena at all higher levels.

Restricting attention to epistemological issues, 'reduction', as noted before, is a type of explanation. 'Reductionism' is usually taken to be either or both of the theses that: (1) in a given domain reductions will be forthcoming; and (2) research programmes should be based on the search for reductions. Here, reductionism will be construed as the conjunction of both these theses. The first makes reductionism an empirical claim: it may fail just as the mechanical philosophy ultimately failed. The second makes reductionism a prescriptive programme for biological research.

Finally, it should be noted that there is one type of question that is ubiquitous in biology and for which there are no straightforward reductionist explanations. Such questions are those of origin: why certain features

Introductory article

Article Contents

- Introduction
- Formal Issues
- Substantive Issues
- Scientific Status
- Research Methodology

of an organism arose during its evolutionary history. These questions are typically answered functionally, appealing to natural selection, or historically, appealing to historical contingencies, or both. Whether such explanations can eventually be subsumed under the reductionist camp, and whether such a project is even biologically interesting, remains doubtful.

Formal Issues

Systematic philosophical analysis of reductionism began with Nagel in 1949 and almost all formal models remain variants of Nagel's model. These models assume that (1) reduction is a relation between theories; and (2) the reduced theory is logically deduced from the reducing one; after (3) terms in the two theories are connected to each other by bridge laws.

All three assumptions of this model have been controversial: (1) Theories are supposed to be sets of universal laws. Yet, in many areas of science where reductions are supposed to be occurring, from the kinetic theory of matter to molecular biology, there seem to be no such laws. Rather, at the level of the reducing discipline, there only are mechanisms. (2) Scientific derivations often involve approximative techniques and numerical calculations that do not satisfy the pristine requirements of logical deductions. (3) The form of the bridge laws has been subject to more philosophical controversy than any other aspect of reduction. At one extreme are those who hold that 'types' in the reduced theory must be connected to 'types' in the reduced one: no single entity at the former level can be connected to many at the lower level (sometimes called multiple realizability). This position is almost certainly too strong to be tenable. It excludes the standard type of situation where macroscopic phenomena are reduced to microscopic ones: to every macrophysical state (say that of a cylinder of gas) there is always an almost infinite number of microphysical states (molecular arrangements of the gas). Another issue has been whether these bridge laws must be biconditionals ('if and only if' claims) since, for explanations to go through, conditionals ('if then' statements connecting the reducing domain to the reduced one) are sufficient. Those who hold the former position are usually motivated by the ontological hope of establishing identities between entities at the two levels.

It is important to note that some of these formal issues are not about reduction *per se* but about the nature of explanation in general, for instance, the role of theories and whether approximations are permissible. It is probably helpful to ignore these issues in epistemological discussions of reduction, in order to concentrate on what additional requirements otherwise acceptable explanations must satisfy to qualify as reductions.

Substantive Issues

Quite independent of the form that reductions must take is the question as to what substantive assumptions are involved in reductions. Two intuitions lie behind attempts to describe certain explanations as reductions: that phenomena in one domain are being explained by – or reduced to – phenomena in another, and that there is a hierarchical representation in which explanations go from the bottom towards the top. These intuitions can be made precise using three criteria: (1) fundamentalism – the explanation of a feature of a system invokes only rules (the 'fundamental rules') from a different, more fundamental realm; (2) abstract hierarchy – the system is represented as a hierarchy of entities with lower level of the hierarchy being regarded as more fundamental than upper ones; and (3) spatial hierarchy – the hierarchy mentioned in (2) is one in physical (rather than some abstract) space.

The three most important types of reduction are: (a) weak reductions: those that only satisfy criterion (1); (b) abstract reductions: those that satisfy both criteria (1) and (2) but not (3); and (c) strong reductions: those that satisfy all three criteria. Genetics provides illustrations of all three of these types, classical genetics of the first two, and molecular genetics of the third.

Consider (the controversial) attempts to explain the variability of a phenotypic trait in a population from the variation at the genetic level on the basis of a high value for the statistic 'broad heritability'. Such explanations, to the extent that they work, are weak reductions. The genetic level is different from the phenotypic one and presumed to be more fundamental since genetic differences are assumed to explain phenotypic differences, but not conversely. The fundamental rule is that which says that genetic and environmental influences on a trait can be factored using the analysis of variance. That the genome has a hierarchical structure plays no role in these explanations. Thus, of the three substantive criteria for reduction, only criterion (1) is satisfied.

In classical genetics, one of the standard ways to attribute a genetic aetiology to a trait is through segregation and linkage analyses. As before, criterion (1) is satisfied. However, segregation and linkage analyses assume Mendel's laws (in the usual diploid case) which, in turn, postulate a hierarchical organization of the genome into linkage groups, individual loci and alleles at those loci. However, and this point should be more widely appreciated than it is, this hierarchy is an abstract one. Mendelian explanations are not committed to any particular physical composition of the genes. Mendel formulated his rules long before the physical basis of heredity was known. The reason why there is sometimes confusion on this issue is because the abstract Mendelian organization of the genome maps approximately on to the physical structure of chromosomes (only approximately, because there can be overlapping genes, genes within genes,

etc., at the physical level). This type of reduction is sometimes called genetic reduction, and the associated reductionist thesis, genetic reductionism.

Finally, in molecular genetics, detailed physical models of genes are constructed and, as explanations proceed from the details of the physical structure and interactions of the parts, strong reductions result. These explanations rely on mechanisms governed chiefly by 'lock-and-key' fits between interacting parts of molecules (for instance, the active site of enzymes). To the extent that these molecular mechanisms explain the replication of chromosomes and thereby show why the Mendelian rules are true, this amounts to a reduction of Mendelian genetics to molecular genetics. However, because such explanations do not conform to the formal requirements of Nagel's model, this putative reduction of Mendelian to molecular genetics has been controversial.

The substantive issues treated so far are epistemological. Turning to substantive issues, vitalism was a doctrine that denied ontological reductionism because it postulated the existence of special forces in living systems. Since its demise, substantive ontological issues have not generally been controversial in biology. Even those who deny the possibility of strong reductions in biology admit that the lower levels determine the upper; no change can occur at an upper level without a change at the lower level. This position is called 'supervenience' in the philosophical literature.

Scientific Status

In this section the current status of reductionism in the various biological subdisciplines will be very briefly indicated. Attention will be restricted to substantive issues, which are the ones of most scientific interest.

Molecular biology

It is in molecular biology that one finds the most significant triumphs of physical reductionism, of the mechanistic view of life that has guided a significant part of biological research since the nineteenth century. How reduction proceeds in molecular genetics has already been indicated in the last section. The same principles apply elsewhere in molecular biology, resulting in strong reductions. For instance, antibodies interact with antigens when there is a fit in shape between the antigen and the active site of the antibody. Two models have been particularly important in underscoring the success of reductionism in molecular biology by providing reductions of phenomena that have traditionally been part of the repertoire of antireductionists: (1) the allostery model shows how cooperative phenomena, as exemplified by the sigmoidal binding curve of haemoglobin and oxygen, can be given a reductionist

explanation; and (2) the operon model shows how phenomena involving feedback can also be similarly explained. What deserves attention, though, is that reduction is to the laws of macromolecular physics and not physics or chemistry at some lower level of organization.

This should not be taken to suggest that all explanations in molecular biology involve strong reductions. In particular, explanations using the concept of information are not reductionist in this sense since rules about information are not lower-level physical rules.

Genetics

The types of reduction that are found in classical genetics have already been discussed in the previous section. Restricting attention to genetic reductions, it is clear that these explanations work in some cases, for instance, in explaining polydactyly or the sickle cell trait in humans. However, genetic reductionism becomes much more controversial when attempts are made to extend it to more complex traits, in particular, human behavioural traits including mental disease traits such as schizophrenia. Prospects for genetic reductionism in these contexts seem dim at present. Genetic reductionism only remains tenable because an adequate theory of development is yet to be formulated. If such a theory emerges, and is based on the primacy of genes, then genetic reductionism will be vindicated.

Evolutionary biology

In the context of reductionism, the issue most in dispute in evolutionary biology is whether evolution at all levels of the taxonomic hierarchy can ultimately be explained by selection (or other evolutionary mechanisms) acting at the level of genes. If so, this leads to the view, popular among population geneticists, that evolution is only a change of gene frequencies. (This position may be viewed as an evolutionary extension of genetic reductionism.) There is little dispute that evolution can be tracked using gene frequencies. However, critics of gene selectionism maintain that this is only book-keeping; selection is supposed to be directly operating at higher taxonomic levels. Most of these critics endorse selection at the level of individual genotypes. However, even higher-level units such as group or kin are probably necessary to explain certain social traits such as altruism.

Ecology

In population ecology, explanations of populational features such as growth rates, relative species compositions, etc., on the basis of the interactions between individuals satisfy the requirements of strong reductions.

The fundamental rules are those that govern the interactions between individuals. In community ecology, systems are usually represented using trophic or food webs. If these have a hierarchical structure, explanations using them are abstract hierarchical reductions; otherwise they are weak reductions. The fundamental rules are those that govern the interactions between species. Since ecosystem ecology is much less clearly defined than either population or community ecology, the status of explanations in it is also less clear. If the fundamental rules used are those involving energy and matter flows, the system usually does not have a hierarchical representation and only weak reductions are possible.

In recent years, an intriguing proposal has been that all ecological phenomena can be explained on the basis of individual-based models. In effect, this says that community and ecosystem ecology is to be reduced to population ecology as a strong reduction. In the past such a claim would have been implausible, given the complexity of most ecological systems. However, the advent of high-speed computation has made this proposal much more plausible. In consonance with usage in the philosophy of the social sciences, this type of reductionism has been called methodological individualism in ecology.

Neurobiology

Because of the traditional interest in the mind–body problem, more philosophical work on reductionism has been done in the context of neurobiology than in any other biological context. At one extreme are claims of strong reduction: mental properties are taken to be properties of brains. Explanation then proceeds by exploiting the anatomy of the brain and the biochemical interaction of parts. This proposal is supported by the fact that increasingly detailed neuroanatomical studies has led to the functional localization of many forms of mental behaviour. However, given the present status of knowledge in the neurosciences, any final commitment to strong reductionism seems unwarranted, even though the search for such reductions continue to constitute fertile research programmes.

At the other extreme are claims that even weak reduction of mental phenomena to neurobiological principles will be impossible. According to this view, mental phenomena only supervene on neurobiological facts; theories of mind must draw on traditions other than those of functional neuroanatomy to be successful, for instance, on assumptions about information storage and manipulation in the computer model of the mind. Somewhere in between these antireductionist claims and strong reductionist claims are models such as those of neural networks. Explanations using these models assume that neuroanatomy matters, but what really matters are not the detailed biochemistry and structure of the interacting parts but, rather, how the

system is organized. In recent years, it has become clear that some mental functions, such as memory, are not localized to unique brain regions. This may indicate that the complexity of the relation between brain and mind may require topological or other forms of systemic nonreductionist explanation. In general, these nonreductionist claims do not deny the supervenience of the mental upon the physical. What is at stake is the epistemological issue of explanation.

Research Methodology

In each of the fields considered above, there is almost complete consensus that reductionist research strategies continue to be useful even if they are not the only ones that should be pursued. What remains in dispute among biologists is whether too much emphasis is being put on reductionist research programmes. Philosophers have pointed out that such research programmes are committed to the principle that the better explanations always emanate from lower levels of organization. One starts at the lowest level and searches for explanations at the next higher level iteratively only if explanations are not found at that level. This is a metaphysical principle that is incompatible with the positivist interpretation of science, which urges a search for the best explanation – one that explains the most phenomena most accurately – irrespective of the level from which the explanation comes. At least in evolutionary biology, it is clear that a reductionist methodology has led to biases against groups and higher taxa as units of selection. Finally, it should be noted that biology is replete with methodologies that are not reductionist, for instance, the statistical analysis of traits in populations. It follows that a claim that biology operates successfully only with reductionist research programme is clearly untenable.

Further Reading

- Churchland PS (1986) *Neurophilosophy*. Cambridge, MA: MIT Press.
- Coleman W (1971) *Biology in the Nineteenth Century*. Cambridge: Cambridge University Press.
- Hull D (1972) *Philosophy of Biological Science*. Englewood Cliffs, NJ: Prentice-Hall.
- Huston M, DeAngelis D and Post W (1988) New computer models unify ecology. *BioScience* **38**: 682–691.
- Machamer P, Darden L and Craver CF (2000) Thinking about mechanisms. *Philosophy of Science* **67**: 1–25.
- Nagel E (1961) *The Structure of Science*. New York: Harcourt, Brace and World.
- Rosenberg A (1985) *The Structure of Biological Science*. Chicago: University of Chicago Press.
- Rosenberg A (1994) *Instrumental Biology*. Chicago: University of Chicago Press.

- Sarkar S (1996) Biological information. In: Sarkar S (ed.) *The Philosophy and History of Molecular Biology: New Perspectives*. Dordrecht, The Netherlands: Kluwer.
- Sarkar S (1998) *Genetics and Reductionism*. New York: Cambridge University Press.
- Schaffner K (1993) *Discovery and Explanation in Biology and Medicine*. Chicago: University of Chicago Press.
- Shimony A (1987) The methodology of synthesis: parts and wholes in low-energy physics. In: Kargon R and Achinstein P (eds) *Kelvin's Baltimore Lectures and Modern Theoretical Physics*. Cambridge, MA: MIT Press.
- Sober E (1984) *The Nature of Selection*. Chicago: University of Chicago Press.
- Wimsatt WC (1976) Reductive explanation: a functional account. In: Cohen RS and Sonné R (eds) *PSA-1974*. Dordrecht, The Netherlands: Reidel.
- Wimsatt WC (1980) Reductionist research strategies and their biases in the units of selection controversy. In: Nickles T (ed.) *Scientific Discovery: Case Studies*. Dordrecht, The Netherlands: Reidel.