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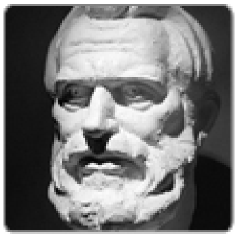

Reductionism in Biology

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Introduction

Reductionism concerns a set of ontological and epistemological claims, and methodological strictures based on them, about the relationship between two different scientific domains. The critical assumption is that one of these domains is privileged over the other in the sense that the concepts, rules, laws, and other elements of the privileged domain can be used to specify, constitute, or account for those of the other "reduced" domain. This specification often consists of explanation, such that the "reducing" domain is epistemically privileged over the reduced one. Explanations of this type are "reductionist" (or, are "reductions") and reductionism is then the thesis that such explanations will always be forthcoming or at least are possible in principle. Reductionism is most plausible if the entities of the reduced domain can be interpreted as arising from (e.g., as aggregates of) entities of the reduced domain. This ontological claim is controversial but motivates many reductionist theses and associated scientific research programs. Thus, epistemological and ontological claims about reductionism have the methodological implication that they should govern and guide scientific research. When such research proves to be fruitless over a period of time, the associated reductionist claims themselves become suspect. Although issues connected with reductionism arise in the physical and social sciences, most attention to reductionism in philosophy of science over the last few decades has focused on the biological sciences, especially after the advent of molecular biology made it plausible to believe that biological phenomena can be uniformly explained (in detail) from their physical basis. However, the program of finding such explanations has a long philosophical history often couched in terms of seeking "mechanical," "mechanistic," or "materialistic" explanations. The contrast here is with traditional vitalism and various forms of teleology and holism.

Historical Background

The possibility of reductionism goes back at least to the mechanical philosophy of the 17th century. Some proponents explicitly claimed that all physical properties of bodies would be explained by contact interactions between their constituent parts. This theme, and how it played out in the history of science, was analyzed in detail by Stein 1958. Mechanical explanations were called "structural" by McMullin 1978 and interpreted as paradigmatically reductionist by Sarkar 1989. In the 17th century, William Harvey's work (Harvey 1981) on wholes and parts, and especially on the heart as a pump and the mechanical circulation of blood, was most important though Harvey also exhibits significant influences from Aristotle (see Distelzweig 2016). René Descartes disputed Harvey's claims from the perspective of his "mechanical philosophy" (Des Chene 2001). In the context of 19th-century German biology, Lenoir 1982 characterizes various combinations of mechanism and holism exhibited by researchers. Brigandt and Love 2017 traces implicit discussions of reductionism back to Aristotle.

Brigandt, Ingo, and Alan C. Love. "Reductionism in Biology." In *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta. Stanford, CA: Stanford University, 2017.

An encyclopedia entry that contains a brief discussion (Section 2) of reductionism in the history of philosophy, including Aristotle and the Scholastics, the Cartesians and other mechanists, and the teleomechanists of the 19th century before turning to 20th-century and later philosophy of science.

Des Chene, Dennis. *Spirits and Clocks: Machine and Organism in Descartes*. Ithaca, NY: Cornell University Press, 2001.

Incisive and comprehensive analysis of how Descartes applied his mechanical philosophy to biological questions with variable success.

Distelzweig, Peter M. "'Mechanics' and Mechanism in William Harvey's Anatomy: Varieties and Limits." In *Early Modern Medicine and Natural Philosophy*. Edited by Peter Distelzweig, Benjamin Goldberg, and Evan R. Ragland, 117–140. Dordrecht, The Netherlands: Springer, 2016.

Useful analysis of the complex nuances in Harvey's thinking about mechanism and teleology in life science inquiry.

Harvey, William. *Disputations Touching on the Generation of Animals*. Translated by Gwenneth Whitteridge. Oxford: Blackwell, 1981.

The most complete account of Harvey's views on the relations between parts and wholes in organisms. Useful in comparison to his better-known works on the circulation of blood. Originally published in 1651.

Lenoir, Timothy. *The Strategy of Life: Teleology and Mechanics in Nineteenth Century German Biology*. Chicago: University of Chicago Press, 1982.

Seminal study of how 19th-century German biologists mixed and matched themes from mechanistic or materialistic styles of explanations and various forms of teleology and holism.

McMullin, Ernan. "Structural Explanation." *American Philosophical Quarterly* 15 (1978): 139–147.

Characterizes mechanical explanation as structural in nature and contrasts it to nomothetic and genetic explanations. It shows exactly what was special about the mechanical philosophy.

Sarkar, Sahotra. "Reductionism and Molecular Biology: A Reappraisal." PhD diss., University of Chicago, 1989.

Reductionism in contemporary molecular biology is viewed as the logical development of the mechanical philosophy of the 17th century. Also contains the most detailed history of reductionism in 20th-century philosophy of science so far available.

Stein, Howard. "Some Philosophical Aspects of Natural Science." PhD diss., University of Chicago, 1958.

An extensive assessment of the rise and fall of the mechanical philosophy. Though most of the discussion focuses on developments in physics, Stein notes how the biology of the 1940s and 1960s marks one culmination of the program of the mechanical philosophy.

Philosophical Analyses

Analyses of reductionism in the natural sciences have been influenced heavily by the logical empiricist approach exemplified in Nagel

1961. Reduction is viewed as a type of inter-theoretic explanation where a reducing theory explains a reduced one in the sense that the latter is to be logically deduced from the former. Schaffner 1967 influentially modified this account to allow a reducing theory to correct a reduced one. Distinct approaches to explanatory reduction are developed in Wimsatt 2007, Kaiser 2015, and Sarkar 2004. Brigandt and Love 2017 provides an overview of relevant issues.

Brigandt, Ingo, and Alan C. Love. "Reductionism in Biology." In *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta. Stanford, CA: Stanford University Press, 2017.

Provides a very useful and comprehensive entry to the literature on reductionism in biology. However, formal dimensions of theoretical reduction do not get detailed critical attention.

Kaiser, Marie I. *Reductive Explanation in the Biological Sciences*. Cham, Switzerland: Springer, 2015.

A practice-oriented account: reductive explanations must (1) rely only on features at a lower level than the phenomenon, (2) appeal only to physical parts ("internal") of the phenomenon, and (3) represent each part in isolation from its original context. Also includes a systematic treatment of meta-philosophical issues that underlie different approaches.

Nagel, Ernest. *The Structure of Science: Problems in the Logic of Scientific Explanation*. New York: Harcourt, Brace, & World, 1961.

Mature development and canonical statement of theory reduction (especially chapters 11–12); remains the most important source for what is widely regarded as the classical account. Considers both the formal and non-formal conditions of reduction (see Nagel 1961 under Conceptual Issues: Theory, Explanation, Methodology).

Sarkar, Sahotra. *Molecular Models of Life: Philosophical Papers on Molecular Biology*. Cambridge, MA: MIT, 2004.

Includes four papers that are primarily on reduction (chapters 1–4) and two others that also analyze the role of reductionism in evolutionary biology (chapters 5, 14).

Schaffner, Kenneth F. "Approaches to Reduction." *Philosophy of Science* 34 (1967): 137–147.

Reviewed existing accounts of reduction. Modified Nagel 1961 to allow the reducing theory to correct a reduced one in the sense that what is derived from the former is a theory that is "strongly analogous" to the latter. Became the most common source for the classical account of theory reduction.

Wimsatt, William C. *Re-Engineering Philosophy for Limited Beings: Piecewise Approximations to Reality*. Cambridge, MA: Harvard University Press, 2007.

Includes four papers explicitly on reductionism (chapters 9–12) and most papers at least implicitly deal with the challenges posed by complexity to reductionism. Themes treated include levels of organization, mechanistic explanation, upper-level dynamical autonomy, reductionist problem-solving methodologies and their biases, aggregativity, and emergence.

Classic Sources

Explicit analysis of reductionism in the natural sciences begins with the work of Nagel 1949 which developed a model of reduction concordant with the logical empiricist philosophy of science. Reduction is viewed as a type of inter-theoretic explanation: a reducing theory explains a reduced one in the sense that the latter is to be logically deduced from the former. Nagel 1951 applies this analysis to biology. Woodger 1952 provides a very similar account. Different approaches to theory reduction were offered by Kemeny and Oppenheim 1956 and Suppes 1957. Oppenheim and Putnam 1958 presents a comprehensive reductionist agenda to unify all the sciences. These analyses are synthesized in Schaffner 1967. Nickles 1973 distinguishes reductions between levels of organization and those that occur within one level of organization, for instance, when a predecessor theory is reduced to its successor in some special cases.

Kemeny, John G., and Paul Oppenheim. "On Reduction." *Philosophical Studies* 7 (1956): 6–19.

Intended as an alternative to the model of Nagel 1949. However, views reduction essentially as the replacement of a theory by a superior one in the sense of being more systematized and predictively better. Unclear why such a relationship should be called a reduction.

Nagel, Ernest. "The Meaning of Reduction in the Natural Sciences." In *Science and Civilization*. Edited by Robert C. Stauffer, 99–138. Madison: University of Wisconsin Press, 1949.

The first detailed statement of what became the classic logical empiricist account of reduction as the logical derivation of the theories of the reduced discipline from the theories of the reducing one.

Nagel, Ernest. "Mechanistic Explanation and Organismic Biology." *Philosophy and Phenomenological Research* 11 (1951): 327–338.

Used the Nagel 1949 account to analyze the situation in biology. Showing a somewhat remarkable lack of familiarity with the then recent developments in biology, it is pessimistic about prospects of reductionist explanation in biology in the near future.

Nickles, Thomas. "Two Concepts of Inter-theoretic Reduction." *Journal of Philosophy* 70 (1973): 181–201.

Was influential in distinguishing between reductions within a level of organization ("intra-level" reductions) and between levels of organization ("inter-level" reductions). Argued that, in the former case, epistemic privilege went in a direction opposite to that of the reduction.

Oppenheim, Paul, and Hilary Putnam. "The Unity of Science as a Working Hypothesis." In *Concepts, Theories, and the Mind-Body Problem*. Edited by Herbert Feigl, Michael Scriven, and Grover Maxwell, 3–36. Minneapolis: University of Minnesota Press, 1958.

A classic statement of a reductionist interpretation of science which is supposed to consist of the reduction of each special science to the one at the next lower level of organization until the microphysical level is reached. Reduction thus results in the unity of science.

Schaffner, Kenneth F. "Approaches to Reduction." *Philosophy of Science* 34 (1967): 137–147.

Reviews the details and relationships of the different analyses presented in this section. Offers a synthetic analysis that recognizes the contributions of each, which then became the canonical version of the Nagelian approach.

Suppes, Patrick. *Introduction to Logic*. New York: Van Nostrand, 1957.

Provides an alternative to Nagel's account of reduction; essentially, one theory is reducible to another if there is a formal isomorphism between the two. Unclear why this is reduction: the theories may be about different contents, and neither theory would have epistemic or other privilege in the case of an isomorphism. Nevertheless, influenced many formal developments in the reduction literature.

Woodger, Joseph H. *Biology and Language*. Cambridge, UK: Cambridge University Press, 1952.

Independently offers an account of reduction similar to that of Nagel 1949. Primarily of historical interest because Woodger was the first to attempt an axiomatization of genetics. Perhaps even more strongly influenced by logical positivism than Nagel.

Contemporary Touchstones

Hooker 1981 provides a detailed analysis of theory reductionism with several modifications of the traditional picture due to Nagel, Schaffner, and others. Schaffner 1993 represents the most complete defense of theory reduction in biology; specifically, allows the reduced theory to correct the reducing one. Wimsatt 1976 initiates an entirely new approach to reduction, with mechanistic explanations based on a modified model of statistical explanation due to Wesley Salmon. Sarkar 1998 argues that the question of reduction should be kept independent from the logical form of explanation: what is at stake are the additional criteria a successful explanation must satisfy to comprise a reduction. Mayr 1982 introduces distinctions between constitutive, explanatory, and theory reductionism, which Sarkar 1992 uses to classify the accounts of reduction then available. Sarkar 2015 reviews the current status of Nagelian reduction with an emphasis on the significance of approximation.

Hooker, Clifford A. “Towards a General Theory of Reduction.” *Dialogue* 20 (1981): 35–59, 201–236, 496–529.

Views theory reduction as the most important type of reduction. Moreover, deals in detail with cases that do not strictly conform to Nagel’s canonical account. What the reducing theory is supposed to provide is an “image” of the reduced theory and not the reduced theory itself or a corrected version of the reduced theory.

Mayr, Ernst. *The Growth of Biological Thought*. Cambridge, MA: Harvard University Press, 1982.

Primarily a historical work but includes an explicit argument for the autonomy of biology from the physical sciences (chapter 2). Distinguishes between theory reductionism, explanatory reductionism, and constitutive reductionism (which amounts to token physicalism). Biology is supposed to embrace the third category but not the first two. Important because of Mayr’s perhaps undue influence on the philosophy of biology.

Sarkar, Sahotra. “Models of Reduction and Categories of Reductionism.” *Synthese* 91 (1992): 167–194.

Used the categorization of theory, explanatory, and constitutive reductionism of Mayr 1982 to provide a comprehensive critical review of extant analyses of reduction. Sarkar 1998 abandons Mayr’s schematism.

Sarkar, Sahotra. *Genetics and Reductionism*. New York: Cambridge University Press, 1998.

Attempted a new critical analysis of accounts of reduction. Sharply distinguished between formal questions (regarding the logical form of an explanation) and substantive questions (regarding the factual assumptions of an explanation) and emphasized the role of the latter in determining which explanations are reductions. Also, distinguished between epistemological and ontological issues with an emphasis on the former.

Sarkar, Sahotra. “Nagel on Reduction.” *Studies in History and Philosophy of Science* 53 (2015): 43–56.

A systematical reappraisal of Nagelian reduction in light of major criticisms and recent defenses (see, e.g., Dizadji-Bahmani, et al. 2010, under Formal Structure). Defends Nagel’s pluralism about the logical form and status of connections between the reduced and reducing theories. Argues explicitly for the significance of different types of approximation.

Schaffner, Kenneth F. *Discovery and Explanation in Biology and Medicine*. Chicago: University of Chicago Press, 1993.

Includes further development and modification of his Nagel-inspired account to include both theory reduction and theory replacement (especially chapter 9). The reduced theory is also allowed to modify the reducing one. The new account is applied to a wide variety of biological cases.

Wimsatt, William C. "Reductive Explanation: A Functional Account." In *PSA 1974: Proceedings of the 1974 Meeting of the Philosophy of Science Association*. Edited by Robert S. Cohen, Clifford A. Hooker, Alexander C. Michalos, and James van Evra, 671–710. Dordrecht, The Netherlands: Reidel, 1976.

Perhaps the first significant departure from Nagelian accounts. Accepted the distinction of Nickles 1973 (cited under Classic Sources) between intra-level and inter-level reductions, but argues that although the former may be approximated by Nagel's model, the latter involve the heuristic use of inter-level identifications to find mechanistic explanations based on a modified version of Wesley Salmon's model of explanation (in terms of causal rather than statistical relevance) and cost-benefit considerations.

Conceptual Issues: Theory, Explanation, Methodology

The classic account of reduction in Nagel 1961 is based on a logical empiricist construal of theories as formalized in first-order logic. Reduction is viewed as having the structure of a deductive-nomological explanation but with the *explanandum* being a law rather than an individual fact. Nagel imposed two conditions on reduction: connectability and derivability. The former required that terms of the reduced and reducing theories be connected (by what came to be known as bridge laws); Nagel allowed the connections to have the form of either conditionals or biconditionals and their status to be analytic, synthetic, or conventional. Causey 1977, Schaffner 1967, and Sklar 1967 require the bridge laws to be synthetic identities. The latter condition required the logical deduction of the reduced theory from the reducing one. To facilitate derivability, Schaffner 1967 allowed the reducing theories to correct a reduced one. Hempel 1969 is an early recognition of the divergent issues raised by ontological and epistemological questions. The papers in Wimsatt 2007 display a different development of ideas about reduction that emphasizes questions of complexity, emergence, and causal explanation.

Causey, Robert L. *The Unity of Science*. Dordrecht, The Netherlands: Reidel, 1977.

In contrast to Nagel 1961, Causey argued that the connections between terms of the reduced and reducing theories (that is, the bridge laws) must be synthetic identities so that reductions can contribute to scientific unification.

Hempel, Carl G. "Reduction: Linguistic and Ontological Issues." In *Philosophy, Science, and Method: Essays in Honor of Ernest Nagel*. Edited by Sidney Morgenbesser, Patrick Suppes, and Morton White, 179–199. New York: St. Martin's, 1969.

The importance of this paper lies in its recognition that ontological commitments entailed by reductions are distinct from the epistemological question of derivability of a reduced theory from a reducing one. The contrast here is with Nagel 1961.

Nagel, Ernest. *The Structure of Science: Problems in the Logic of Scientific Explanation*. New York: Harcourt, Brace, & World, 1961.

Besides the well-known formal conditions, three non-formal conditions make a reduction non-trivial (chapter 11). (1) Postulates of the reducing theory must be supported by empirical evidence with probative force. (2) The reducing theory must be "fertile" in suggesting developments of the reduced theory. (3) Both theories must be such that the reduction aids further development of the reduced theory. Includes a substantial discussion of parts and wholes (chapter 12).

Schaffner, Kenneth F. “Approaches to Reduction.” *Philosophy of Science* 34 (1967): 137–147.

Modified the account of Nagel 1961 to allow reducing theories to correct a reduced one by generating a logically derivable theory that was strongly analogous to the original theory being reduced. The connections between entities in the reduced and reducing theories were required to be synthetic identities.

Sklar, Lawrence. “Types of Inter-theoretic Reduction.” *British Journal for the Philosophy of Science* 18 (1967): 109–124.

In contrast to Nagel 1961, argued that the connections between terms of the reduced and reducing theories (that is, the bridge laws) must be synthetic identities, and also that the reduced theory was not derivable from the reducing theory since the latter corrected the former.

Wimsatt, William C. *Re-Engineering Philosophy for Limited Beings: Piecewise Approximations to Reality*. Cambridge, MA: Harvard University Press, 2007.

Four of the papers collected here discuss substantive aspects of reduction and related issues, including aggregativity and emergence (chapters 9–12). However, all papers are at least partly relevant to discussions of reductionism because of an overarching concern for complexity. Considers the role of problem-solving heuristics and their biases. Inter-level explanations involve mechanistic explanations utilizing inter-level identities and localizations.

Formal Structure

Until the late 1980s almost all discussions of reduction focused on the logical form that reductions should take and assumed that reduction was a relation between theories. The canonical Nagelian model was modified (e.g., a reduced theory, after being appropriately connected to the reducing one, was derived from it) or restricted (e.g., assumptions about the logical form of the relation between theories) by different authors. Wimsatt 1976 and Balzer and Dawe 1986a and Balzer and Dawe 1986b offer alternative formal treatments, while Sarkar 1998 argues that these formal aspects of reduction are not as important as substantive ones. Dizadji-Bahmani, et al. 2010 defends a modified Nagelian account.

Balzer, Wolfgang, and Christopher M. Dawe. “Structure and Comparison of Genetic Theories: (1) Classical Genetics.” *British Journal for the Philosophy of Science* 37 (1986a): 55–69.

Breaks with Nagel’s and similar accounts of reduction insofar as theories are formalized in a set-theoretic formalism rather than in first-order logic (in the interest of avoiding unnecessary formal complexity).

Balzer, Wolfgang, and Christopher M. Dawe. “Structure and Comparison of Genetic Theories: (2) The Reduction of Character-Factor Genetics to Molecular Genetics.” *British Journal for the Philosophy of Science* 37 (1986b): 177–191.

Reduction between theories is assumed to require establishing a formal (essentially deductive) relation between models of the core of theories that are formalized in the sense of Balzer and Dawe 1986a. This necessary condition is then supplemented by an informal requirement that the theories in question be about the same subject.

Dizadji-Bahmani, Foad, Roman Frigg, and Stephan Hartmann. “Who’s Afraid of Nagelian Reduction?” *Erkenntnis* 73 (2010): 393–412.

Defends formal aspects of a modified Nagelian account of reduction. Attempts to answer criticisms of this model comprehensively.

Sarkar, Sahotra. *Genetics and Reductionism*. New York: Cambridge University Press, 1998.

Argues that the question of reduction should be separated from the question of the form of an explanation and, as a consequence, the two questions are independent (chapters 2–3). Claimed that these questions of form were less philosophically and scientifically interesting than the substantive questions of what a reduction assumed.

Wimsatt, William C. "Reductive Explanation: A Functional Account." In *PSA 1974: Proceedings of the 1974 Meeting of the Philosophy of Science Association*. Edited by Robert S. Cohen, Clifford A. Hooker, Alexander C. Michalos, and James van Evra, 671–710. Dordrecht, The Netherlands: Reidel, 1976.

Viewed successional reduction as a relation to localize similarities and differences in aid of establishing the newer theory. Inter-level reduction seen as a type of causal-mechanistic explanation rather than in terms of laws involving inter-level identifications. Inspired by Wesley Salmon's account of explanation in terms of statistically relevant factors but interpreted relevance as causal in part to advocate for scientific realism.

Substantive Content

Since the 1980s, many analyses of reduction have focused on the substantive assumptions (e.g., hierarchical relationships among parts and wholes) made in a reduction rather than on its logical form (e.g., connectability and derivability). However, even earlier, Nagel had emphasized the importance of non-formal, that is, substantive, conditions required for a reduction not to be trivial (e.g., discovering unexpected connections between experimental laws). Kauffman 1971 provided a compelling account of part-whole explanation and Wimsatt 1976 emphasized similar issues. Waters 1990 focused on part-whole relations in reductions. Sarkar 1998 distinguished between various forms of reduction on the basis of the substantive assumptions they embody, especially about the epistemic privilege of the reducing claims and part-whole relations. Machamer, et al. 2000 analyzes mechanisms that would be viewed as providing part-whole explanation by Kauffman 1971 or Wimsatt 1976. Hüttemann and Love 2011 adds causal considerations including temporality. Kaiser 2015 rejects temporality but emphasizes part-whole relations and their representation. Weber 2005 discusses substantive aspects of reduction in the context of experimental work in biology.

Hüttemann, Andreas, and Alan C. Love. "Aspects of Reductive Explanation in Biological Science: Intrinsicality, Fundamentality, and Temporality." *British Journal for Philosophy of Science* 62 (2011): 519–549.

Uses three criteria to distinguish possible types of part-whole reductions: intrinsicality, whether the entities invoked in explanations are internal to the system being explained; fundamentality, or epistemic privilege; and temporality, requiring past events explain future ones. In many ways extends the analysis of Sarkar 1998.

Kaiser, Marie I. *Reductive Explanation in the Biological Sciences*. Cham, Switzerland: Springer, 2015.

Focuses on three conditions of reductive explanations observable in scientific practice: (1) reliance only on features at a lower level than the phenomenon, (2) an appeal only to physical parts ("internal") of the phenomenon, and (3) each part is represented in isolation from its original context.

Kauffman, Stuart A. "Articulation of Parts Explanations in Biology and the Rational Search for Them." In *PSA 1970: Proceedings of the Biennial Meeting of the Philosophy of Science Association*. Edited by Robert S. Cohen and Roger C. Buck, 257–272. Dordrecht, The Netherlands: Reidel, 1971.

Does not explicitly call the model presented a "reduction." However, lays out a careful account of how wholes are to be explained in terms of their parts and describes interesting heuristics to guide searches for such explanations. Probably the first modern account of mechanistic explanation. Makes a compelling case for viewing biological systems in terms of abstract cybernetic models.

Machamer, Peter, Lindley Darden, and Carl F. Craver. "Thinking about Mechanisms." ***Philosophy of Science*** **67 (2000): 1–25.**

Though couched in terms of "mechanisms," this account can be interpreted as providing an analysis of part-whole reductions. Was influential in establishing mechanisms as a centrally important topic in the philosophy of biology.

Sarkar, Sahotra. ***Genetics and Reductionism*****. New York: Cambridge University Press, 1998.**

Three criteria distinguish different types of reductions: fundamentality (epistemic privilege); hierarchical organization of parts and wholes; and spatial instantiation of the abstract hierarchy (chapter 3). Argues these issues are philosophically and scientifically more interesting than issues related to logical form. All reductions must satisfy first criterion; satisfying the third logically requires satisfying second. Various types of reduction can be characterized by these constraints.

Waters, C. Kenneth. "Why the Antireductionist Consensus Won't Survive: The Case of Classical Mendelian Genetics." In ***PSA 1990: Proceedings of the Biennial Meeting of the Philosophy of Science Association*****. Vol. 1. Edited by Arthur Fine, Mickey Forbes, and Linda Wessels, 125–139. East Lansing, MI: Philosophy of Science Association, 1990.**

Another analysis that emphasizes the significance of part-whole relations in reductions. Argues against the scientific interest of purely formal questions about reduction. The analysis is based on a difference principle with the difference-makers operating at the reducing (lower) level of organization.

Weber, Marcel. ***Philosophy of Experimental Biology*****. New York: Cambridge University Press, 2005.**

Discusses reductionism and explanation in the context of experimental biology with most of the focus being on molecular biology (especially chapter 2). Defends reductionism but also emphasizes functional explanation. Analyzes reductionism as a research strategy in that context.

Wimsatt, William C. "Reductive Explanation: A Functional Account." In ***PSA 1974: Proceedings of the 1974 Meeting of the Philosophy of Science Association*****. Edited by Robert S. Cohen, Clifford A. Hooker, Alexander C. Michalos, and James van Evra, 671–710. Dordrecht, The Netherlands: Reidel, 1976.**

Assumes "compositionality" for inter-level reduction and thus implicitly provides a model for part-whole reduction.

Research Methodology

The pursuit of reduction also can guide research either because of a commitment that reductions will be forthcoming (that is, a commitment to reductionism) or because the only research methodology available in a given context is reductionist. Wimsatt 2006 and Schaffner 1993 make the positive case for the use of reductionist methodology in some contexts; Wimsatt 1980 documents when reductionist modeling strategies may lead us astray. Bechtel and Richardson 2010 implicitly discusses part-whole reductionism as a research strategy and its manifestation across different sciences is detailed in Winther 2011. Weber 2005 provides many detailed examples. However, reductions (that is, explanations that are appropriately interpreted as reductionist) may also occur even though the methodology of research is not explicitly reductionist. Schaffner 1974 argues that this is the case in molecular biology.

Bechtel, William, and Robert C. Richardson. *Discovering Complexity: Decomposition and Localization as Strategies in Scientific Research*. Cambridge, MA: MIT, 2010.

Extended discussion of the use of what amounts to part-whole reductionism as a research strategy in different areas of biology. This edition contains a substantial new introduction reviewing work since its original publication in 1993.

Schaffner, Kenneth F. "The Peripherality of Reductionism in the Development of Molecular Biology." *Journal of the History of Biology* 7 (1974): 111–139.

Argues that the pursuit of theory reduction in the classical (Nagelian) sense was not central to the historical development of molecular biology even though the structure of the piecemeal explanations that resulted can be interpreted as approximating his account of theory reduction.

Schaffner, Kenneth F. *Discovery and Explanation in Biology and Medicine*. Chicago: University of Chicago Press, 1993.

Offers a more pluralistic account of the role of reductionist research strategies in molecular and other areas of biology (chapter 9).

Weber, Marcel. *Philosophy of Experimental Biology*. New York: Cambridge University Press, 2005.

Includes a sustained discussion of reductionism as a research strategy in the design of experiments, mainly in the context of molecular biology (chapter 2).

Wimsatt, William C. "Reductionistic Research Strategies and Their Biases in the Units of Selection Controversy." In *Scientific Discovery: Case Studies*. Edited by Thomas Nickles, 213–259. Dordrecht, The Netherlands: D. Reidel, 1980.

Enumerates reductionist heuristic modeling strategies and argues that they have biased discussions of the units of selection in evolutionary biology by misrepresenting the phenomena, with lower-level units (especially genes) receiving illegitimate preference, and group selection receiving less attention than deserved.

Wimsatt, William C. "Reductionism and Its Heuristics: Making Methodological Reductionism Honest." *Synthese* 151 (2006): 445–475.

Distinguishes successional and interlevel reduction as serving different functions that explain their logical differences, and distinguishes both from aggregativity. Discusses reductionist heuristics used in constructing inter-level theory and explanations, and their biases.

Winther, Rasmus G. "Part-Whole science." *Synthese* 178 (2011): 397–427.

Argues that part-whole science is a distinctive style of scientific investigation that appears across life science disciplines and results in part-whole explanations. Emphasizes differences in aims, norms, and what is being explained through scrutiny of practices for abstracting kinds of parts.

Scientific Status

The plausibility of reductionism varies between the biological sub-disciplines. The most plausible situations are at the cellular and sub-cellular levels where the relevant empirical details have been worked out and the item being reduced (e.g., cell) is close in scale to the item reductively explaining it (e.g., molecular constituents). At the other end of the biological hierarchy—ecosystems and higher levels—

the situations are less plausible because of missing empirical details or substantial gaps in scale. However, even cases where scales are commensurate, such as a reductionist explanation of an ecosystem in terms of its constituent species, are controversial. Wimsatt and Sarkar 2006 and Brigandt and Love 2017 provide overviews. Hüttemann and Love 2016 compares and contrasts forms of reduction in physics and biology; O'Malley, et al. 2014 illustrates a variety of multilevel research strategies found within molecular inquiry into biological systems. Tauber and Sarkar 1992 interprets the Human Genome Project as blind reductionism that has gone too far.

Brigandt, Ingo, and Alan C. Love. "Reductionism in Biology." In *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta. Stanford, CA: Stanford University Press, 2017.

An extensive encyclopedia entry that treats many of the biological sub-disciplines (besides some of the history of reductionism). Some areas, especially ecology and neurobiology, are not analyzed extensively. However, the areas treated are done so with philosophical depth.

Hüttemann, Andreas, and Alan C. Love. "Reduction." In *The Oxford Handbook of Philosophy of Science*. Edited by Paul Humphreys, 460–484. New York: Oxford University Press, 2016.

Traces thinking about reduction from discussions of the unity of science and micro-reduction among logical empiricists through their development in Nagelian reduction and subsequent diversification within different areas of physics and biology. Emphasizes the diversity of asymmetrical, reductive relations across the natural sciences.

O'Malley, Maureen A., Ingo Brigandt, Alan C. Love, et al. "Multilevel Research Strategies and Biological Systems." *Philosophy of Science* 81 (2014): 811–828.

Reviews diverse research strategies found in contemporary molecular life sciences and characterizes their conceptual, methodological, and explanatory dimensions in microbial ecology, systems biology, protein research, and developmental biology.

Tauber, Alfred I., and Sahotra Sarkar. "The Human Genome Project: Has Blind Reductionism Gone Too Far?" *Perspectives in Biology and Medicine* 35 (1992): 220–235.

Critique of the Human Genome Project (HGP) at an early stage of its execution. Argues that the reductionist claims of many prominent proponents of the HGP were demonstrably misleading. Predicts that the HGP will have little immediate impact on medicine. Instead, sequencing as part of standard ongoing molecular biology is defended as better science policy.

Wimsatt, William C., and Sahotra Sarkar. "Reductionism." In *The Philosophy of Science: An Encyclopedia*. Vol. 2. Edited by Sahotra Sarkar and Jessica Pfeifer, 696–703. New York: Routledge, 2006.

Provides a succinct critical overview of reductionism in the empirical sciences; biology is one of the cases treated. The intention is to unify discussions of reductionism across the different sciences.

Molecular Biology

Though almost all analyses suggest that reductionism was made more plausible than ever before by developments in molecular biology, several of the seminal figures in the field were motivated by anti-reductionist goals. This historical development shows how complex the issues surrounding reductionism can be. This section focuses (but is not limited to) some of the highlights of this work including Bohr 1933, Delbrück 1966, and Stent 1968. In contrast, Schrödinger 1944 laid out an influential reductionist agenda. Sarkar 1989 and Waters 1990 challenged the prevalent anti-reductionist consensus in the philosophy of biology that had solidified by the 1980s. Rosenberg 2006 offers a unique defense of explanatory reduction that justifies the privileging of the molecular level for all biological explanations by appeal to the principle of natural selection operating on the molecular level. Waters 2008 shifts attention away from theoretical explanation to investigative reasoning by arguing that molecular genetics substantially increased what biologists could do experimentally.

Bohr, Niels. "Light and Life." *Nature* 131 (1933): 421–423, 457–459.

Here, one of the founders of quantum physics argues that living phenomena will not be reduced to physics but will require complementary modes of explanation as, allegedly (and controversially), was also the case in the quantum domain.

Delbrück, Max. "A Physicist Looks at Biology." In *Phage and Origins of Molecular Biology*. Edited by John Cairns, Gunther S. Stent, and James D. Watson, 9–22. Plainview, NY: Cold Spring Harbor Laboratory, 1966.

How one of the founders of molecular biology (motivated by Bohr's 1933 speculations on complementarity in biology) pursued an anti-reductionist agenda though, by and large, the experimental context he adopted required that the research methodology remain reductionist (and be based on macromolecular physics).

Rosenberg, Alexander. *Darwinian Reductionism: Or, How to Stop Worrying and Love Molecular Biology*. Chicago: University of Chicago Press, 2006.

Argues that biology is being reduced to the molecular level at which natural selection operates as a physical principle. This principle of natural selection is supposed to be the only genuine law in biology.

Sarkar, Sahotra. "Reductionism and Molecular Biology: A Reappraisal." PhD diss., University of Chicago, 1989.

This dissertation, along with Waters 1990, challenged the prevailing consensus in the 1980s among philosophers of biology that reductionism did not capture either the research strategy of molecular biology or the structure of explanations it offered. Mainly about the structure of explanations.

Schrödinger, Erwin. *What Is Life? The Physical Aspect of the Living Cell*. Cambridge, UK: Cambridge University Press, 1944.

Highly influential statement of a reductionist agenda for biology. Argues that the current laws of physics could not explain living phenomena but, once these were supplemented by new laws of physics (which would operate on both living and non-living matter), physics would account for the phenomena of life.

Stent, Gunther S. "That Was the Molecular Biology that Was." *Science* 160 (1968): 390–395.

One of the founders of molecular biology interprets the early history of the field as being founded on the hope that the field would produce results that were paradoxical from the perspective of physics.

Waters, C. Kenneth. "Why the Antireductionist Consensus Won't Survive: The Case of Classical Mendelian Genetics." In *PSA 1990: Proceedings of the Biennial Meeting of the Philosophy of Science Association*. Vol. 1. Edited by Arthur Fine, Mickey Forbes, and Linda Wessels, 125–139. East Lansing, MI: Philosophy of Science Association, 1990.

Challenged the prevailing anti-reductionist consensus in the 1980s among philosophers of biology. Argued that this consensus was built entirely on philosophical rather than biological arguments.

Waters, C. Kenneth. "Beyond Theoretical Reduction and Layer-Cake Antireduction: How DNA Retooled Genetics and

Transformed Biological Practice." In *The Oxford Handbook of Philosophy of Biology*. Edited by Michael Ruse, 238–262. New York: Oxford University Press, 2008.

Emphasizes how the investigative practices of genetics were transformed by the advent of molecular biological tools that increased the range of available experimental interventions and contributed to the success of the corresponding explanations.

Genetics – Classical and Molecular

Because many of the successes of early molecular biology (in the 1950s and 1960s) came from molecular genetics, most of the discussion of reductionism in biology has focused on the question of whether classical genetics (Mendelism as modified by discoveries such as linkage, incomplete dominance, etc.) was being reduced to molecular genetics, macromolecular physics, or, more broadly, physics and chemistry. Schaffner 1969 made a case for theory reduction though Schaffner 1974 argued that the research strategy followed in molecular biology was not reductionist. Hull 1972 and Kitcher 1984 were important papers that denied reduction was occurring and thereby contributed to the anti-reductionist consensus of the 1980s. Waters 1990 and Sarkar 1998 defended reduction but did not necessarily interpret it as a relationship between theories. Balzer and Dawe 1986a and Balzer and Dawe 1986b defend reductionism in genetics.

Balzer, Wolfgang, and Christopher M. Dawe. "Structure and Comparison of Genetic Theories: (1) Classical Genetics." *British Journal for the Philosophy of Science* 37 (1986a): 55–69.

Formalizes what is taken to be the core of classical genetics using set-theoretic predicates as a prelude for a reduction which would involve, essentially, the derivation of a model of this core from a corresponding model of (the core of) molecular genetics.

Balzer, Wolfgang, and Christopher M. Dawe. "Structure and Comparison of Genetic Theories: (2) The Reduction of Character-Factor Genetics to Molecular Genetics." *British Journal for the Philosophy of Science* 37 (1986b): 177–191.

Continues the analysis begun in Balzer and Dawe 1986a. Uses a formalization of the core of molecular genetics to reduce character-factor genetics by deriving a model of the core of the latter from the former.

Hull, David L. "Reductionism in Genetics—Biology or Philosophy?" *Philosophy of Science* 39 (1972): 491–499.

Argues that molecular genetics is replacing rather than reducing classical (Mendelian) genetics. Criticism of the potential reduction of the latter to the former is based on the claim that the relations between terms of the two theories are many-many because of multiple realizability and context-dependence. First paper of the anti-reductionist consensus that emerged during this period.

Kitcher, Phillip. "1953 and All That: A Tale of Two Sciences." *Philosophical Review* 93 (1984): 335–373.

An influential paper in the 1980s which denied that molecular biology offers a reduction of classical (Mendelian) genetics. Assuming that reduction must be classical (Nagelian) theory reduction, argues that the formal requirements cannot be satisfied. Emphasizes context-dependence and introduces a category of explanatory extension to replace that of reduction in these contexts.

Sarkar, Sahotra. *Genetics and Reductionism*. New York: Cambridge University Press, 1998.

Attempts a comprehensive analysis of reductionism in genetics (chapters 4–6). Argues that complex physical and, especially, behavioral traits cannot be reduced to (classical) genetics. Distinguishes between genetic and physical reductionism, the latter involving part-whole reductions in which the rules performing the reduction are those of macromolecular physics. Argues for the salience of physical reductionism in biology, including the reduction of classical genetics to molecular biology.

Schaffner, Kenneth F. "The Watson-Crick Model and Reductionism." ***British Journal for the Philosophy of Science*** **20 (1969): 325–348.**

Argues that the double helix model of DNA provides an exemplary case of theory reduction.

Schaffner, Kenneth F. "The Peripherality of Reductionism in the Development of Molecular Biology." ***Journal of the History of Biology*** **7 (1974): 111–139.**

Argues that the explicit pursuit of (theory) reduction was not central to the research strategy of molecular biology. Nevertheless, such reductions are what molecular biology is supposed to provide.

Waters, C. Kenneth. "Why the Antireductionist Consensus Won't Survive: The Case of Classical Mendelian Genetics." In ***PSA 1990: Proceedings of the Biennial Meeting of the Philosophy of Science Association*****. Vol. 1. Edited by Arthur Fine, Mickey Forbes, and Linda Wessels, 125–139. East Lansing, MI: Philosophy of Science Association, 1990.**

Important for forcefully challenging the anti-reductionist consensus in the 1980s among philosophers of biology that molecular biology was not leading to a reduction of classical (Mendelian) genetics. Argued that critics of reductionism were only offering philosophical arguments with no concern for the scientific context.

Cell and Developmental Biology

Beyond genetics, the obvious areas in which molecular biology could potentially lead to reductions are cell and developmental biology. The former has received less attention than the latter with Hüttemann and Love 2011 being a notable exception. Griesemer 2000 argues that genetics can be reduced to development. Gilbert and Sarkar 2000 and Laubichler and Wagner 2001 critique strong reductionist claims in developmental biology; the latter is a response to Rosenberg 1997. Robert 2004 emphasizes the contextual nature and complexity of many explanations in developmental biology.

Gilbert, Scott F., and Sahotra Sarkar. "Embracing Complexity: Organicism for the 21st Century." ***Developmental Dynamics*** **219 (2000): 1–9.**

Attempts to discuss both the successes and limitations of reductionism. The limitations are interpreted as a modest victory of a mitigated form of organicism.

Griesemer, James. "Reproduction and the Reduction of Genetics." In ***The Concept of the Gene in Development and Evolution: Historical and Epistemological Perspectives*****. Edited by Peter Beurton, Rapahael Falk, and Hans-Jörg Rheinberger, 240–285. New York: Cambridge University Press, 2000.**

Argues that genetics can be reduced to developmental biology (which, as was traditionally done, is taken to include reproduction). Based on the observation that Mendel's laws and other inheritance processes are a result of developmental processes during reproduction.

Hüttemann, Andreas, and Alan C. Love. "Aspects of Reductive Explanation in Biological Science: Intrinsicality, Fundamentality, and Temporality." ***British Journal for Philosophy of Science*** **62 (2011): 519–549.**

Treats cell biology insofar as it discusses reductionism in the context of the protein folding problem which is perhaps the most famous unsolved problem of molecular biology. A careful discussion of various reductionist assumptions in this context.

Laubichler, Manfred D., and Gunther P. Wagner. "How Molecular is Molecular Developmental Biology? A Reply to Alex Rosenberg's Reductionism Redux: Computing the Embryo." *Biology and Philosophy* 16 (2001): 53–68.

A response to Rosenberg 1997; explicitly argues for a presumed anti-reductionist consensus among philosophers of biology. Emphasizes the importance of functional explanations which are presumed to present a problem for reductionism.

Robert, Jason S. *Embryology, Epigenesis, and Evolution: Taking Development Seriously*. New York: Cambridge University Press, 2004.

Emphasizes the contextual nature and complexity of many explanations in developmental biology and thereby attempts to restrict the role that can be played by any form of reductionism.

Rosenberg, Alexander. "Reductionism Redux: Computing the Embryo." *Biology and Philosophy* 12 (1997): 445–470.

Presents a case for reductionism in molecular developmental biology arguing that it challenges the anti-reductionist consensus that was still presumed to exist among philosophers of biology.

Evolutionary Biology

A variety of issues related to reductionism have been extensively discussed in the philosophy of evolutionary biology. Sarkar 1998 interpreted the so-called modern synthesis as a reduction of biometry to Mendelism. Tabery 2004 points out that Yule was attempting a reduction in the opposite direction. Many philosophers (and a few biologists) have worked on the units of selection problem, with the reductionists attempting to model selection at the lowest level possible (e.g., Williams 1985), and their opponents arguing for a more pluralistic strategy—see, e.g., Sober 1984 and Okasha 2006. Wimsatt 1980 points out biases resulting from reductionist research strategies.

Okasha, Samir. *Evolution and the Levels of Selection*. Oxford: Oxford University Press, 2006.

A careful and thorough exploration of the units and levels of selection problem. Implicitly includes a discussion of issues connected with reductionism.

Sarkar, Sahotra. *Genetics and Reductionism*. New York: Cambridge University Press, 1998.

Argues that what has been called the modern synthesis was in fact a reduction, with biometry being reduced to Mendelian genetics through the formulation of quantitative genetics, primarily by Fisher (chapters 4–5).

Sober, Elliott. *The Nature of Selection: Evolutionary Theory in Philosophical Focus*. Cambridge, MA: MIT, 1984.

Clarifies a range of philosophical issues associated with evolutionary theory including the units of selection problem. Only implicitly deals with reductionism.

Tabery, James. "The 'Evolutionary Synthesis' of George Udny Yule." *Journal of the History of Biology* 37 (2004): 73–101.

Argues that Yule's project was an attempt to reduce Mendelism to biometry which is why it had little, if any, influence on the subsequent development of evolutionary theory based on theoretical population genetics.

Williams, George C. “A Defense of Reductionism in Evolutionary Biology.” *Oxford Surveys in Evolutionary Biology* 2 (1985): 1–27.

A spirited defense of genic reductionism with the gene taken to be the fundamental level at which selection operates. The argument is based on the claim that tracking gene frequencies suffices to describe evolutionary processes. An earlier book by Williams in 1966 initiated the reductionist turn in evolutionary biology.

Wimsatt, William C. “Reductionistic Research Strategies and Their Biases in the Units of Selection Controversy.” In *Scientific Discovery: Case Studies*. Edited by Thomas Nickles, 213–259. Dordrecht, The Netherlands: D. Reidel, 1980.

Argues that genetic reductionism (see, e.g., Williams 1985) is inadequate for a dynamically sufficient theory of evolutionary change and that reductionist assumptions in the form of problem-solving heuristics applied in the construction of mathematical models have biased research on the units of selection in evolutionary biology, with lower-level units (especially genes) receiving illegitimate preference and group selection receiving less attention than deserved.

Ecology

Though ecology has long been a bastion for holists and other anti-reductionists, reductionism is central to one of the most important recent research programs in ecology—using individual-based models (i.e., tracking the relevant properties of each individual of a species). Huston, et al. 1988 lays out this agenda. Sarkar 2005 and Sarkar 2016 explore the philosophical ramifications of this approach; more critical work is important and would not go unnoticed.

Huston, Michael, Donald DeAngelis, and Wilfred Post. “New Computer Models Unify Ecological Theory.” *BioScience* 38 (1988): 682–691.

Makes the case for the potential impact of individual-based models in ecology which are supposed to have finally become tractable due to advances in computational ability. These models are also expected to unify different subfields within ecology. A compelling vision of where ecological research should go.

Sarkar, Sahotra. *Biodiversity and Environmental Philosophy: An Introduction*. New York: Cambridge University Press, 2005.

Argues that the advent of individual-based models and geographic information systems technology are transforming both ecology and its use for biodiversity conservation. The discussion can be interpreted as a mitigated defense of reductionism in ecology.

Sarkar, Sahotra. “Ecology.” In *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta. Stanford, CA: Stanford University, 2016.

Includes an explicit defense of reductionism in ecology in the form of the use of individual-based models. Sees this as establishing population ecology in a foundational role in ecology in the same way as population genetics provides a foundation for evolution.

Neurobiology

All discussions of the mind-body problem are at least implicitly discussions of reductionism. The pieces annotated here will be limited to work that is explicitly part of ongoing discussions of reductionism in the philosophy of science; work that seems to fall within the philosophy of mind rather than the philosophy of science is excluded. Wimsatt 1976 is one of the pioneering works falling into the category treated here. Churchland 1986 defends standard theory reductionism. Bickle 2003, Craver 2007, and Gillett 2016 are informed by recent developments in neuroscience.

Bickle, John. *Philosophy and Neuroscience: A Ruthlessly Reductive Approach*. Dordrecht, The Netherlands: Kluwer, 2003.

Defense of reductionism in neuroscience that tries to show how emerging explanations affect traditional problems in the philosophy of mind. Concerned with letting reductions emerge from the details of molecular and sub-cellular explanations rather than using any prior philosophical model of reduction.

Churchland, Patricia S. *Neurophilosophy*. Cambridge, MA: MIT, 1986.

A strong defense of the use of theory reductionism in neurobiology. By and large, neurobiology is not only supposed to reduce psychology but also to provide a replacement for it. Thus, it is a form of eliminative reductionism.

Craver, Carl F. *Explaining the Brain: Mechanisms and the Mosaic Unity of Neuroscience*. Oxford: Oxford University Press, 2007.

Defense of reductionism insofar as it is concerned with mechanisms. Argues that these mechanisms unify neuroscience. Rich in scientific detail.

Gillett, Carl. *Reduction and Emergence in Science and Philosophy*. Cambridge, UK: Cambridge University Press, 2016.

Engages both scientific and philosophical debates while identifying drawbacks in both discussions with an emphasis on successful part-whole explanations in the sciences. Offers a novel theoretical framework that distinguishes four senses of composition (comprising, realization, implementation, and constitution), and is responsive to developments in neurobiology and other allied sciences.

Wimsatt, William C. "Reductionism, Levels of Organization and the Mind-Body Problem." In *Consciousness and the Brain: Scientific and Philosophic Strategies*. Edited by Gordon Globus, Grover Maxwell, and Irwin Savodnik, 205–267. New York: Plenum, 1976.

Analyzes the mind-body problem using his causal relevance model of reduction and the heuristic role of inter-level identifications to localize mechanistic explanations of upper-level phenomena, arguing for a non-eliminative "emergent reductionism." Includes a new analysis of levels of organization and a nuanced discussion of problems associated with the localization of the mind in the brain.

Criticisms

Even after the advent of molecular biology, the possibility of reductionism has been denied in many analyses. Many critics have asserted the autonomy of biology though only a few have offered serious argumentation. Most critics have relied on context-dependence of physical or molecular explanations in biology or on multiple realizability (or both). Brigandt and Love 2017 discusses many of these issues, while Maclaurin 2011 argues that "reduction" is too heterogeneous to be conceptually helpful.

Brigandt, Ingo, and Alan C. Love. "Reductionism in Biology." In *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta. Stanford, CA: Stanford University, 2017.

Discusses many of the objections to reductionism in biology in detail. Also treats some of the alternatives to reductionism and what it considers new directions in analyzing inter-field relations.

Maclaurin, James. "Against Reduction: A Critical Notice of *Molecular Models: Philosophical Papers on Molecular Biology* by Sahotra Sarkar." *Biology and Philosophy* 26 (2011): 151–158.

This notice argues that "reduction" is far too heterogeneous a term to be of much help in discussions of molecular (and presumably other parts of) biology. Criticizes Brigandt and Love 2017 for trying to include all of this heterogeneity under the label of "reduction."

Assertions of Autonomy

Claims for the autonomy of living phenomena from physical ones have always been part of the life sciences and sometimes have been influential in guiding research programs, such as in explorations of functional organization. The success of molecular biology in the late 20th century finally posed a credible challenge to this view. Nevertheless, sophisticated philosophical arguments for autonomy were offered, for instance, by Fodor 1974 (for all the special sciences) and Rosenberg 1978; these were sometimes accompanied by less compelling arguments but stronger assertions of autonomy (e.g., Mayr 2004). Considerations from physical theory can also support claims of autonomy in biology in a way consistent with reduction (e.g., Batterman 2017).

Batterman, Robert W. "Autonomy of Theories: An Explanatory Problem." *Nous* (2017).

Argues for multiple realizability and the dynamical autonomy of upper-level phenomena in a way that is grounded in physical theory and universality, yet consistent with reductionism. Generalizable to many upper-level accounts, including biology.

Fodor, Jerry A. "Special Sciences, or the Disunity of Sciences as a Working Hypothesis." *Synthese* 28 (1974): 97–115.

Highly influential paper that argued for the autonomy of each special science. The argument was partly based on denying that types at multiple levels were smoothly connected to each other.

Mayr, Ernst. *What Makes Biology Unique? Considerations on the Autonomy of a Scientific Discipline*. New York: Cambridge University Press, 2004.

Arguments for the autonomy of biology by a prominent evolutionary biologist long noted for his anti-reductionism. However, not as philosophically important insofar as most discussions lack depth.

Rosenberg, Alexander. "The Supervenience of Biological Concepts." *Philosophy of Science* 45 (1978): 368–386.

Argues that biological concepts supervene on physical ones, denying any explanatory role for the latter with regard to the former. The argument relies on multiple realizability (see Multiple Realizability).

Context-Dependence

What a particular molecular mechanism does depends on the context in which it occurs. While this claim is undeniable, it is less clear why it poses a problem for reductionism unless an account of reduction is accompanied by a claim that the context cannot be introduced as part of the explanation. This seems to be what Hull 1972 and Kitcher 1984 have in mind, though no argument for the claim is offered. Kaiser 2015 supports the claim from explanatory practices that attempt to ignore or simplify the context and fail because a system's behavior is genuinely context-dependent. Wimsatt 2007 explores how aggregativity assumptions used in theory construction can lead to mistaken assessments of context-dependence. Robert 2004 emphasizes the complexity of developmental contexts.

Hull, David L. "Reductionism in Genetics—Biology or Philosophy?" *Philosophy of Science* 39 (1972): 491–499.

Argues that context-dependence results in a one-many relation between the lower and upper levels and that this precludes (theory) reduction.

Kaiser, Marie I. *Reductive Explanation in the Biological Sciences*. Cham, Switzerland: Springer, 2015.

Argues that biological practice assumes reductive explanations must ignore or simplify the environmental factors for a system and study its parts in isolation (chapter 6).

Kitcher, Phillip. "1953 and All That: A Tale of Two Sciences." *Philosophical Review* 93 (1984): 335–373.

Argues for context-dependence and, therefore, the absence of appropriate laws in both classical and molecular genetics. This supposedly prevents theory reduction.

Robert, Jason S. *Embryology, Epigenesis, and Evolution: Taking Development Seriously*. New York: Cambridge University Press, 2004.

Emphasizes the complexity of many developmental contexts where that complexity (at least at present) is not characterizable at the molecular level. A nuanced discussion of the limits of reductionism in developmental biology.

Wimsatt, William C. *Re-Engineering Philosophy for Limited Beings*. Cambridge, MA: Harvard, 2007.

Chapter 12 is an extended discussion of aggregativity and emergence, demonstrating how simplifying assumptions of aggregativity can lead to the underestimation or misrepresentation of context-dependence.

Multiple Realizability

Especially in the context of part-whole reductions, a single upper-level entity can be realized by several lower-level ones, which may be quite heterogeneous in some cases. The issue has been perceived by many critics as posing a problem for reductionism, especially if the upper-level entity is a type and the lower-level ones are tokens (or types). This point was raised early by Hull 1972 in his critique of the potential reduction of classical genetics to molecular genetics and also was part of Kitcher's influential critique (Kitcher 1984). Rosenberg 1978 essentially argues for the supervenience of biological concepts on the same basis. There have been many responses, including the claim of Schaffner 1993 that types are actually being connected to types. Reductionism is defended by Weber 2005, whereas Sober 1999 finds the existence of heterogeneity at the lower level scientifically interesting, and Wimsatt 2006 argues that multiple-realizability is inevitable given stable, upper-level phenomena.

Hull, David L. "Reductionism in Genetics—Biology or Philosophy?" *Philosophy of Science* 39 (1972): 491–499.

Argues that multiple realizability results in a many-one relation between the lower and upper levels and that this precludes (theory) reduction.

Kitcher, Phillip. “1953 and All That: A Tale of Two Sciences.” *Philosophical Review* 93 (1984): 335–373.

Argues that multiple realizability precludes explanation in molecular biology because molecular accounts do not capture natural kinds corresponding to those in classical (Mendelian) genetics.

Polger, Thomas W., and Lawrence A. Shapiro. *The Multiple Realization Book*. New York: Oxford University Press, 2016.

Comprehensive survey of issues related to multiple realization with an emphasis on empirical factors in formulating an account of the mind-brain relationship. Acknowledges widespread multiple realizability, but argues that it provides no barrier for reduction.

Rosenberg, Alexander. “The Supervenience of Biological Concepts.” *Philosophy of Science* 45 (1978): 368–386.

Multiple realizability is supposed to result in the supervenience of biological concepts on physical ones; though no biological change can occur without a physical change, the relation between the two realms is so complex as to preclude explanation and, therefore, reduction.

Schaffner, Kenneth F. *Discovery and Explanation in Biology and Medicine*. Chicago: University of Chicago Press, 1993.

Argues that higher-level types correspond to lower-level types thus nullifying the multiple realizability objection to reductionism (chapter 9). However, he does not address the problem that a single higher-level type could correspond to multiple lower-level types.

Sober, Elliott. “The Multiple Realizability Argument against Reductionism.” *Philosophy of Science* 66 (1999): 542–564.

Points out that multiple realizability means heterogeneity at the reducing (typically lower) level. Embraces this heterogeneity by arguing that it is itself scientifically interesting.

Weber, Marcel. *Philosophy of Experimental Biology*. New York: Cambridge University Press, 2005.

Argues that the existence of connections between tokens at different levels is sufficient to ensure reduction (chapter 2).

Wimsatt, William C. “Reductionism and Its Heuristics: Making Methodological Reductionism Honest.” *Synthese* 151 (2006): 445–475.

Argues that multiple realizability is predictable and explicable in any cases with stable, upper-level phenomena. Different ranges of multiple realizability emerge from the articulation of different levels of mechanistic organization between the lower and upper levels considered.

Emergence and New Directions

Although many philosophers have assumed that reduction and emergence are mutually exclusive, others provide arguments for their complementarity, especially in complex systems (e.g., Wimsatt 2007). Recent work in condensed matter physics, systems biology, and complex organization has led to an explosive growth of interest in emergence and integration (e.g., Humphreys 2016; Mitchell 2009). A good source of relevant papers on emergence is Bedau and Humphreys 2008. Some of these writers see their accounts as both reductionist and emergentist, explaining novel higher-level phenomena while accounting for their autonomy. For relevant discussion related to computation, see the separate *Oxford Bibliographies* in Philosophy article Computational Science.

Bedau, Mark A., and Paul Humphreys, eds. ***Emergence: Contemporary Readings in Philosophy and Science*****. Cambridge, MA: MIT, 2008.**

A rich and comprehensive collection of historical and contemporary papers by philosophers and scientists. The scientists defending emergence come mostly from condensed matter physics and focus on explanations of novel qualitative phenomena, while those opposing it work in high-energy physics. Predominantly concentrates on physics rather than biology.

Humphreys, Paul. ***Emergence: A Philosophical Account*****. New York: Oxford University Press, 2016.**

A systematic review of ideas and analyses of emergence from multiple viewpoints. Offers a sustained argument for an account that is consistent with reductionist approaches, while including both static and temporal dimensions.

Mitchell, Sandra D. ***Unsimple Truths: Science, Complexity and Policy*****. Chicago: University of Chicago Press, 2009.**

A systematic argument that complex systems require different analytical tools from those employed in the study of simpler systems, including a different conception of scientific laws, analyses of emergence and self-organization, and diverse complementary explanations that yield an "integrative pluralism."

Wimsatt, William C. ***Re-Engineering Philosophy for Limited Beings: Piecewise Approximations to Reality*****. Cambridge, MA: Harvard University Press, 2007.**

Urges "emergent reductionism" with robust levels of organization and pluralistic perspectives (chapter 9) as elements in multi-level mechanistic explanations (chapter 10). Emergence (chapter 12) is treated as a system property that depends on the mode of organization of parts, or a failure of criteria for aggregativity. These act as heuristics in classifying modes of organization. Illustrated with detailed examples in theory construction.

Self-Organization

Self-organization refers to how system behaviors or patterns emerge from non-specific interactions among lower-level components, such as in the behavior of ensembles of randomly constructed networks. Thus, the system behavior is a function of generic patterns of component interaction that may be isomorphic across diverse phenomena (e.g., gene networks and human social networks). Although methodological reductionism in the sense of decomposing a system into parts is important for claims about self-organization, there is no localization of causal responsibility to individual components as typically expected for reductionist explanations (Bechtel and Richardson 2010, chapter 9). Camazine, et al. 2001 provides a thorough survey of self-organization phenomena in biology and Kirschner, et al. 2000 details its molecular manifestation. A classic (though difficult to read) statement of the theoretical significance of self-organization, especially as a rival to natural selection, is found in Kauffman 1993. The core ideas were first articulated in Kauffman 1969.

Bechtel, William, and Robert C. Richardson. ***Discovering Complexity: Decomposition and Localization as Strategies in Scientific Research*****. Cambridge, MA: MIT, 2010.**

Chapter 9 focuses on self-organization as a case where part-whole reductionism in the sense of a research strategy breaks down because no localization of causal responsibility to component parts results.

Camazine, Scott, Jean-Louis Deneubourg, Nigel R. Franks, James Sneyd, Guy Theraulaz, and Eric Bonabeau. *Self-Organization in Biological Systems*. Princeton, NJ: Princeton University Press, 2001.

A helpful survey of self-organization phenomena that are manifested in different biological systems at a variety of levels of organization.

Kauffman, Stuart A. "Metabolic Stability and Epigenesis in Randomly Constructed Genetic Nets." *Journal for Theoretical Biology* 22 (1969): 437–467.

First paper to make use of ensemble modeling; offers arguments for self-organization rather than biological selection as a source of biological order.

Kauffman, Stuart A. *The Origins of Order: Self-Organization and Selection in Evolution*. New York: Oxford University Press, 1993.

Collects decades of research by Kauffman (though not always consistently) on gene-control networks and other complex systems. A resource full of models and ideas about self-organization (rather than a well-ordered systematic exposition), including several that have widespread application in diverse areas.

Kirschner, Marc, John Gerhart, and Tim Mitchison. "Molecular 'Vitalism.'" *Cell* 100 (2000): 79–88.

Recognizes a conceptual link between self-organization and traditional discussions of vitalism (e.g., limitations of the machine analogy for living systems). Catalogues molecular level phenomena that exhibit self-organization, such as self-assembly and spontaneous symmetry breaking.

Systems Biology

Attempts to catalogue every part and interaction in a cellular context to explain higher level functional properties (e.g., metabolism) are central to the nascent discipline of systems biology. Whether this is stereotypically reductionist or evidence of a more holistic style of explanation is controversial. Boogerd, et al. 2007 introduces many of the relevant issues that arise from the use of reductionist methods to study highly complex systems. Green 2017 is a systematic overview of the most current research and Green, et al. 2017 is a detailed study of how network analyses offer a different approach to understanding the complex dynamics of living systems.

Boogerd, Fred C., Frank J. Bruggeman, Jan-Hendrik S. Hofmeyr, and Hans V. Westerhoff, eds. *Systems Biology: Philosophical Foundations*. Amsterdam: Elsevier, 2007.

Philosophers and scientists address a variety of topics prominent in the rise of systems biology, including reductionism, predictability, emergence, robustness, complexity, synthetic biology, and historical relations to cybernetics.

Green, Sara, ed. *Philosophy of Systems Biology: Perspectives from Scientists and Philosophers*. Dordrecht, The Netherlands: Springer, 2017.

A comprehensive survey of major conceptual issues in systems biology with special emphasis on themes related to reductionism, including holism, complexity, and emergence.

Green, Sara, M. Şerban, Raphael Scholl, N. Jones, Ingo Brigandt, and William Bechtel. "Network Analyses in Systems Biology:

New Strategies for Dealing with Biological Complexity.” *Synthese* (2017).

Contrasts network analyses that rely on graph theoretic tools with decomposition and localization research strategies associated with mechanistic explanation for understanding biological complexity. Emphasizes how network analyses are used to comprehend system dynamics and how these differ from standard reductionist strategies.

Integration

Reduction is an asymmetric relation between two different scientific domains where the reducing domain is privileged over the reduced domain. An increasing demand for and scrutiny of multidisciplinary explanations that involve coordinating or unifying diverse epistemic resources encourages the examination of relations like integration where the fundamentality of a domain is relativized to the evaluative standards for a scientific question or research program. Darden and Maull 1977 is one early exemplar of this idea in terms of interfield theories that combine different domains; Wimsatt 1974 argues that complexity requires bringing together different theoretical perspectives, such as anatomy, physiology, and genetics, to bear on a common problem without reduction. Craver 2007 exemplifies this type of analysis for mechanisms in neuroscience. Subsequent work relaxed the emphasis on theory: Mitchell 2002 focuses on the integration of idealized causal models; Grantham 2004 analyzes interconnections for heuristics and data; O’Malley and Soyer 2012 describes data and methodological integration in systems biology. Love 2008 concentrates on how the structure of research problems organize explanatory integration across domains; Brigandt 2010 develops and expands on this theme.

Brigandt, Ingo. “Beyond Reduction and Pluralism: Toward an Epistemology of Explanatory Integration in Biology.” *Erkenntnis* 73 (2010): 295–311.

Extends the analysis in Love 2008 by showing how different research problems not only require the integration of several domains but also yield variable judgments about which domain is more fundamental in explanations and only requires combining domains transiently (rather than permanently).

Craver, Carl F. *Explaining the Brain: Mechanisms and the Mosaic Unity of Neuroscience*. Oxford: Oxford University Press, 2007.

Rejects traditionally conceived reduction and emphasizes the integration of different disciplinary approaches (“mosaic unity”) in elucidating mechanisms in neuroscience.

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Wimsatt, William C. "Complexity and Organization." In ***PSA-1972: Proceedings of the 1972 Biennial Meeting of the Philosophy of Science Association*****. Edited by Kenneth F. Schaffner and Robert S. Cohen, 67–86. Dordrecht, The Netherlands: Reidel, 1974.**

Distinguishes descriptive and interactional complexity in terms of different non-isomorphic part decompositions used in different theoretical perspectives and the need to combine explanatory factors from these different descriptions in solving a common problem. Anticipates many of the conclusions subsequently made common in accounts of multi-perspectivalism or pluralism.

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