Reduction

Andreas Hüttemann

Alan C. Love

Abstract

Reduction and reductionism have been central philosophical topics in analytic philosophy of science for more than six decades. Together they encompass a diversity of issues from metaphysics and epistemology. This article provides an introduction to the topic that illuminates how contemporary epistemological discussions took their shape historically and limns the contours of concrete cases of reduction in specific natural sciences. The unity of science and the impulse to accomplish compositional reduction in accord with a layer-cake vision of the sciences, the seminal contributions of Ernest Nagel on theory reduction and how they strongly conditioned subsequent philosophical discussions, and the detailed issues pertaining to different accounts of reduction that arise in both physical and biological science (e.g., limit-case and part-whole reduction in physics, the difference-making principle in genetics, and mechanisms in molecular biology) are explored. The conclusion argues that the epistemological heterogeneity and patchwork organization of the natural sciences encourages a pluralist stance about reduction.

Keywords

composition, limit-case reduction, Ernest Nagel, mechanisms, part-whole reduction, theory reduction

Reduction and reductionism have been central philosophical topics in analytic philosophy of science for more than six decades. Together they encompass a diversity of issues from metaphysics (e.g., physicalism and emergence) and epistemology (e.g., theory structure, causal explanation, and methodology). "Reduction" usually refers to an asymmetrical relationship between two items (e.g., theories, explanations, properties, etc.) where one item is *reduced* to another. The nature of this relationship has been characterized in distinct ways for different sets of items: reductive relations between theories have often been understood in terms of logical derivation, whereas reductive relations between properties have sometimes been understood in terms of identity or supervenience. Depending on how the relationship is characterized, one can speak of successful reductions when the asymmetrical relationship is established or manifest, and unsuccessful reductions when for some reason the relationship does not hold. "Reductionism" usually refers to a more general claim or assumption about the existence, availability, or desirability of reductions in an area of research. For example, if particular kinds of reductions are established routinely in molecular biology and constitute a major part of its explanatory capacity, then reduction*ism* can be used as a descriptive label (molecular biology pursues reductionist explanations or has a reductionist methodology).

Arguments for and against reductionism often trade in several different meanings of reduction simultaneously or assume that a particular construal is primary, but the relationship between different conceptions of reduction is complex, and there are few if any entailment relations among them. The specialization trend in philosophy of science, whereby philosophers have increasingly concentrated on actual scientific practices and controversies, has shifted debates away from providing a uniquely correct account of *what* reduction is and toward *why* or *how* scientists pursue reductions in more localized contexts. As a consequence, a rift has grown between metaphysical and epistemological questions because the former often invoke "in principle" considerations about what a completed science *would* be able to say, whereas the latter emphasizes "in practice" considerations that temper the metaphysical inferences one might draw, in part because we find both successful and unsuccessful reductions of different kinds in scientific practice. Thus an argument establishing a particular relationship of reduction between two items in an area of science does not necessarily generalize to an argument in favor of reductionism for all items in that area of science or for other areas of science.

It is impossible to adequately summarize the many detailed analyses of reduction and reductionism in different sciences, even when only focused on the natural sciences. Our goal is not to be comprehensive but rather to provide an introduction to the topic that illuminates how contemporary discussions took their shape historically, especially through the work of Ernest Nagel, and limn the contours of concrete cases of reduction in specific natural sciences. To this end, we begin with a discussion of the unity of science and the impulse to accomplish compositional reduction in accord with a layer-cake vision of the sciences (Section 1). Next, we review Nagel's seminal contributions on theory reduction and how they strongly conditioned subsequent philosophical discussions (Section 2). Then we turn to detailed issues that arise from analyzing reduction in different sciences. First, we explore physical science by explicating different accounts of reduction (e.g., limit reduction and part-whole reduction) and probing their applicability to cases from condensed matter physics and quantum mechanics (Section 3). Second, we explore biological science by rehearsing how an antireductionist consensus grew out of the juxtaposition of genetics with a refined Nagelian view of theory reduction and then subsequently dissipated into a myriad of perspectives on explanatory reduction that apply across the life sciences, including the growth of mechanism approaches (Section 4). In conclusion, we argue that the epistemological heterogeneity and patchwork organization of the natural sciences encourages a pluralist stance about reduction (Section 5).

1. Unity of Science and Microreduction

A common thread running through different accounts of reduction is a concern with coherence between two or more domains. This has appeared frequently under the guise of unification, such as how different theories fit together and provide a more unified explanation. Whether or not this unification obtained seemed to speak to perennial questions: Are living systems anything over and above physical constituents with suitable organization? Are tables and chairs simply swarms of subatomic particles? Many logical empiricists of the mid-twentieth century officially bracketed such metaphysical questions and approached the issues indirectly. They focused on how these questions would be formulated within the framework of scientific theories: Is biology reducible to physics? Is the macroscopic behavior of objects reducible to the behavior of their microscopic constituents? The working assumption was that it was desirable to counterbalance the increasing specialization of the sciences with a meta-scientific study "promoting the integration of scientific knowledge" (Oppenheim and Putnam 1958, 3). This integration was advanced under the auspices of the "Unity of Science" as an organizing principle pertaining to "an ideal state of science" and "a pervasive trend within science, seeking the attainment of that ideal" (4). The "unity" invoked relied on a complex conception of reduction and a vision of reductionism, and the diversity of issues now seen in philosophical discussions can be understood as a slow disentangling of these interwoven claims.

Logical empiricists conceived of reduction as a form of progress: “The label ‘reduction’ has been applied to a certain type of progress in science . . . replacement of an accepted theory . . . by a new theory . . . which is in some sense superior to it” (Kemeny and Oppenheim 1956, 6–7). Thus the unity of science was underwritten by the progressive reduction of one theory to another (i.e., a form of reductionism). Successful reductions contribute to the goal of unification. The conception of reduction appealed to—“microreduction”—involves establishing explicit compositional relations between the objects in one science (e.g., molecules in chemistry) and its components in another science (e.g., subatomic particles in physics). This picture relies on a hierarchy of levels so that every whole at one level can be decomposed into constituents at a lower level: social groups, multicellular organisms, cells, molecules, atoms, and elementary particles. Theories of objects and their constituents were related in microreductions, which encourages a layer-cake view of the sciences as offering theories at corresponding levels of the compositional hierarchy: sociology, organismal biology, molecular biology, chemistry, and physics. Thus a microreduction reduces one branch of science with a theory of objects in its domain (e.g., chemistry) to another branch of science with a theory of the constituents of those objects in its domain (e.g., physics).

This perspective sets out a clear philosophical agenda: characterize the nature of theory reduction so that assessments can be made of the success (or failure) of microreductions at different hierarchical levels with respect to the trend of attaining the ideal of unification (i.e., reductionism). Associated tasks include explicating the structure of scientific theories, translating the distinct vocabulary of one science into another, and spelling out the derivation of the higher-level science from the lower-level one. Given the predominant view of explanation as a logical derivation of an *explanandum* phenomenon from universal laws and initial conditions (Hempel and Oppenheim 1965[1948]), a successful microreduction was explanatory. Although it might not occur in practice ("whether or not unitary [completed, unified] science is ever attained"; Oppenheim and Putnam 1958, 4), the "in principle" vision was bracing: a fundamental theory of the ultimate constituents of the universe from which we can derive all the theories and laws that pertain to its more complex wholes. An epistemological consequence would be a reduced total number of laws, "making it possible, in principle, to dispense with the laws of [the higher-level science] and explain the relevant observations by using [the lower-level science]" (7).

There are a variety of different claims about reduction contained within this global vision of the unity of science based on microreduction: (a) reduction is a type of progress, (b) reduction is a relation between theories, (c) reduction involves logical derivation, (d) reduction is explanatory, and (e) reduction is compositional (part-whole). Much of the debate about reduction from the 1960s through the 1980s can be described as a disentangling and evaluation of these claims: (a) How should we understand scientific progress? Is it always reductionist in character? (b) What is the structure of theories? Are theories the only thing that can be reductively related? (c) Does reduction always involve logical derivation or should we understand it differently? (d) Is reduction always explanatory? How should we understand what counts as an explanation? (e) Is reduction always compositional or can it sometimes be, for example, causal?

Within the debates surrounding these questions there are at least three identifiable trends: (a) conceptualizing scientific progress required far more than the concepts of reduction developed by logical empiricists; (b) questions about the nature of theory reduction came to predominate through discussions of theory structure (Suppe 1977), whether theories relate logically or otherwise, the empirical inadequacy of a layer-cake view of the sciences, and an unraveling of the consensus about a deductive-nomological view of explanation (Woodward 2011); and, (c) increasing attention to examples from nonphysical sciences called into question whether reduction should be seen as a relation between theories and pertain to composition (Hüttemann and Love 2011; Kaiser 2012; Love and Hüttemann 2011). We ignore (a) in what follows and concentrate on (b) and (c) by reviewing Nagel's influential conception of theory reduction (Section 2), exploring the development of ideas about reduction and explanation in physical science (Section 3), and analyzing biological reasoning that challenged the applicability of theory reduction and encouraged different formulations of explanatory reduction (Section 4).

Oppenheim and other logical empiricists were already aware of a proliferation of notions of reduction: "the epistemological uses of the terms 'reduction', 'physicalism', 'Unity of Science', etc. should be carefully distinguished from the use of these terms in the present paper" (Oppenheim and Putnam 1958, 5). In order to increase clarity regarding the diversity of meanings for reduction and reductionism that have been treated, we offer the following coarse-grained classification scheme (Brigandt and Love 2012, Sarkar 1992).

Metaphysical reduction: This refers to theses like metaphysical reduction*ism* or physicalism, which claim that all higher-level systems (e.g., organisms) are constituted by and obtain in virtue of nothing but molecules and their interactions. Associated concepts include supervenience (no difference in a higher-level property without a difference in some underlying lower-level property), identity (each higher-level token entity is the same as an array of lower-level token entities), emergence (a higher-level entity is not reducible to its constituent molecules and their interactions), and downward causation (a higher-level entity has the capacity to bring about changes in lower-level entities, which is not reducible to its lower-level constituents).

Epistemological reduction: This refers to claims about representation and explanation or methodology. For representation and explanation, issues revolve around the idea that knowledge about higher-level entities can somehow be reduced to knowledge about lower-level entities. Dominant themes include what form the knowledge takes, such as whether it is theories structured in a particular way or other units (e.g., models or concepts), what counts as an explanation, and whether this is manifested similarly in different areas of science. For methodology, issues revolve around the most fruitful tactics for scientific investigation. Should experimental studies always be aimed at uncovering lower-level features of higher-level entities, such as by decomposing a complex system into parts (Bechtel and Richardson 1993)? Although a track record of success might suggest an affirmative answer, the exclusive use of reductionist research strategies may lead to systematic biases in data collection and explanatory models (Wimsatt 2007).

The remainder of our discussion focuses on epistemological reduction with special reference to representation and explanation, beginning with Nagel's influential treatment.

2. Nagel's Account of Reduction

Debates about theory reduction concern the relation of two theories that have an overlapping domain of application. This is typically the case when one theory succeeds another and thereby links reduction to progress, such as by requiring that the new theory predict or explain the phenomena predicted or explained by the old theory (Kemeny and Oppenheim 1956). Ernest Nagel's (1961, ch. 11) account of reduction was the most influential attempt to spell out this idea. It remains the shared background for any contemporary discussion of theory reduction. Nagel conceived of reduction as a special case of explanation: "the explanation of a theory or a set of experimental laws established in one area of inquiry, by a theory usually though not invariably formulated for some other domain" (1961, 338). Explanation was understood along the lines of the deductive-nomological model: "a reduction is effected, when the experimental laws of the secondary science . . . are shown to be logical consequences of the theoretical assumptions . . . of the primary science" (352). Nagel gave two formal conditions that were necessary for the reduction of one theory to another. The first was the condition of *connectability*. If the two theories in question invoke different terminology, connections of some kind need to be established that link their terms. For example, "temperature" in thermodynamics does not appear in statistical mechanics. These connections became known as *bridge laws* and were frequently assumed to be biconditionals that express synthetic identities (e.g., the temperature of an ideal gas and the mean kinetic energy of the gas).

The second condition was *derivability*. Laws of the reduced theory must be logically deducible from laws of the reducing theory. A putative example is provided by the wave theory of light and Maxwell's theory of electromagnetism. Once it was established that light waves are electromagnetic radiation of a certain kind (a bridge law), *connectability* was fulfilled and the wave theory of light could be reduced to Maxwell's theory. Everything the wave theory had to say about the propagation of light could (seemingly) be deduced from Maxwell's theory plus the bridge law (*derivability*). The wave theory becomes a part of Maxwell's theory that describes the behavior of a certain kind of electromagnetic radiation (light waves), though expressed in a different terminology that can be mapped onto Maxwell's terminology (Sklar 1967). Provided this account is correct, the wave theory of light can be reduced to Maxwell's theory of electromagnetism. Thus successful "Nagelian reductions" absorb, embed, or integrate the old theory into the successor theory and reduce the number of independent laws or assumptions that are necessary to account for the phenomena (i.e., just those of the new theory). Although the successful predictions of the old theory concerning the phenomena are retained, one can dispense with its assumptions or laws, at least in principle.

Nagel and other logical empiricists were aware that their conception of reduction was a kind of idealization, but a number of key problems soon surfaced. The first was meaning incommensurability. If the meaning of a theoretical term is partially determined by its context, then terms in the old and new theories will have different meanings. Thus a prerequisite for the condition of derivability is violated (Feyerabend 1962). However, this criticism rested on the controversial assumption that the meaning of theoretical terms derived from the context of the entire theory (meaning holism). The second problem was the absence of bridge laws in the form of biconditionals, especially in biology and psychology. A third problem was the absence of well-structured theories with universal laws; Nagel's account cannot explicate reduction in sciences where theories and laws play a less significant role (see Section 4). Finally, the new theory typically does not recover the predictions of the old theory—and for good reasons, because the new theory often makes *better* predictions. This last objection was particularly influential in debates about theory reduction in physics (see Section 3).

Despite these problems, Nagel's account of reduction served as the primary reference point for almost all debates on reduction and reductionism. This is true for debates about whether chemistry can be reduced to physics (Weisberg, Needham, and Hendry 2011, Hendry and Needham 2007) and whether classical genetics can be reduced to molecular genetics (see Section 4). These debates followed a standard pattern. First, they assumed that if some sort of reductionist claim is true, then the pertinent concept of reduction was Nagelian. Second, it was discovered that Nagelian theory reduction failed to capture the relations between different theories, models, or representations in the field of science under scrutiny. As a consequence, various sorts of antireductionist or nonreductionist claims became popular, but it became apparent that such purely negative claims fail to do justice to the relations under investigation in the natural sciences, which encouraged the development of new conceptions of reduction.

Debates about reduction in philosophy of mind, which were tracked widely by philosophers who did not necessarily work on specific natural sciences, serve as an illustration of how Nagelian theory reduction shaped discussions. When it became apparent that claims about mental states, properties, or events could not be reduced *sensu* Nagel to neurobiology or allied sciences, various forms of nonreductive physicalism became popular. This in turn led to the development of alternative conceptions of reduction in order to characterize the relation between different forms of representations.

For example, it has been argued that the essential desideratum in philosophy of mind is not Nagelian reduction but rather the explanation of bridge laws. What is needed is an explanation of *why* pain is correlated with or identical to the stimulation of certain nerve fibres, which is left unexplained in Nagelian reduction. So-called *functional reduction*, if achieved, would give us a reductive explanation of pain in terms of underlying physical or neurobiological features and thereby provide evidence for a metaphysical reduction of the mental to the physical (Chalmers 1996, Levine 1993, Kim 1998, 2005). Functional reduction consists of three steps: (1) the property *M* to be reduced is given a functional definition of the following form: having *M* = having some property *P* (in the underlying reduction domain) such that *P* performs causal task *C*; (2) the properties or mechanisms in the reduction domain that perform causal task *C* are discovered; and, (3) a theory that explains how the realizers of *M* perform task *C* is constructed (Kim 2005, 101–102).

This account of functional reduction is abstract and not well connected to the actual scientific practices of neurobiology or well anchored in empirical details of concrete examples. In this respect, the discussion in philosophy of mind differs from developments surrounding reduction in philosophy of science. This divergence in part explains why the revival of talk about mechanisms in neuroscience has been associated with a rejection of reduction (see Section 4).

3. Reduction in Physics

3.1. Amending Nagel's Model

When one theory succeeds another in an area of science, the theories typically make contradictory claims. This can be illustrated by what Newtonian mechanics (NM) and the special theory of relativity (STR) have to say about the dependence of momentum on velocity. Figure 1 depicts how, relative to some fixed observer, there is an increasing divergence in the predictions made by NM and STR as the ratio of the velocity of a particle to the velocity of light approaches 1. This divergence indicates that STR makes *better* predictions in certain domains, which is part of the reason why it was accepted as a successor of NM. But if NM and STR make contradictory claims, then they are logically incompatible; NM cannot be deduced from STR. Because STR makes better and contradictory predictions compared to NM, Nagelian theory reduction is incapable of adequately describing the reductive relations between STR and NM.

[INSERT FIGURE 1 NEAR HERE]

In the light of this objection, Kenneth Schaffner (1967, 1969, 1976, 1993) revised and developed the theory reduction framework into the general reduction model (GRM). Schaffner acknowledged that the old or higher-level theory typically could not be deduced from the succeeding or lower-level theory. However, he argued that a suitably corrected version of the higher-level theory should be the target of a deduction from the lower-level theory, assuming there are bridge laws that facilitate connectability. This corrected version of the higher-level theory needs to be *strongly analogous* to the original higher-level theory (Schaffner 1993, 429). Strong analogy or "good approximation" (Dizadji-Bahmani et al. 2010) allows for some divergence in predictions, as well as some amount of meaning incommensurability, but the details of the analogical relation are left unspecified (Winther 2009). More recently, Dizadji-Bahmani and colleagues (2010) have defended a generalized Nagel-Schaffner account (GNS) where the higher-level theory is corrected and the lower-level theory is restricted by the introduction of boundary conditions and auxiliary assumptions. Only then are bridge laws utilized to logically deduce the former from the latter. The GNS account retains the Nagelian idea that reduction consists in subsumption via logical deduction, though it is now a *corrected* version of the higher-level theory that is reduced to a *restricted* version of the lower-level theory.

One might be skeptical about how well GRM or GNS capture actual cases of theory relations because, as Figure 1 illustrates, NM is not a good approximation of STR. GRM and GNS are limited to cases in which pairs of theories have largely overlapping domains of application and are simultaneously held to be valid (Dizadji-Bahmani et al. 2010). Most of the cases that Nagel and Schaffner had in mind do not fall in this range. Additionally, the authors' paradigm case—the reduction of thermodynamics to statistical mechanics—generates problems for this account (see Section 3.2). At best, Nagel's model of reduction, where a higher-level level theory is absorbed into a lower-level theory and cashed out in terms of logical deduction, only applies to a restricted number of theory pairs.

3.2. Limit-Case Reduction

Even though it is false that predictions from NM and STR are *approximately* the same, it is nevertheless true that *in the limit* of small velocities, the predictions of NM approximate those of STR. While Nagelian reduction does *not* apply in the case of NM and STR, physicists use a notion of reduction according to which STR reduces to NM under certain conditions (Nickles 1973).[1] Nickles refers to this latter concept as *limit-case reduction* in order to distinguish it from Nagel's concept of theory reduction. Limit-case reduction often permits one to skip the complexities of STR and work with the simpler theory of NM, given certain limiting conditions.

Limit-case reduction is very different from Nagelian reduction. Not only does it obtain in the converse direction (for Nagelian reduction, NM reduces to STR; for limit-case reduction, STR reduces to NM), but limit-case reduction is also a much weaker concept. Successful Nagelian reduction shows that the old theory can be *embedded* entirely in the new theory, whereas limit-case reduction focuses on two theories that make different predictions about phenomena that converge under special circumstances. Thus limit-case reduction is typically *piecemeal*; it might be possible for one pair of equations from STR and NM to be related by a limit-case reduction, while another pair of equations fails. Further, even though both accounts involve derivation, they differ on what is derived. On Nagel's account, the *laws* of the old or higher-level theory have to be logically deducible from the new theory. For limit-case reduction, the classical equation (as opposed to a particular value) is derived from the STR equation, but this sense of "derivation" refers to the process of obtaining a certain result by *taking a limit process*. So, strictly speaking, it is not the classical *equation* that is logically derived from STR but rather *solutions* of the new equations that are shown to coincide with solutions of the old equations in the limit, and solutions of the new equations are shown to differ from those of the old theory only minimally in the neighborhood of the limit (e.g., Ehlers 1997).

Limit-case reduction aims to explain the past success as well as the continued application of a superseded theory from the perspective of a successor theory. It is a *coherence* requirement that the successes of the old theory should be recoverable from the perspective of the new theory (Rohrlich 1988). Although there are many detailed studies of the relations between thermodynamics and statistical mechanics (e.g., Sklar 1993, Uffink 2007), NM and the general theory of relativity (e.g., Earman 1989, Ehlers

1986, Friedman 1986, Scheibe 1999), and classical mechanics and quantum mechanics (e.g., Scheibe 1999, Landsman 2007), we confine ourselves to some observations about the limit-process that are relevant for all of these cases.

1. If limit-case reductions aim to explain the past successes of an old theory, then not all limits are admissible. The equations of STR may reduce to those of NM in the limit $c \to\infty$ (i.e., the solutions of STR and NM coincide in the limit $c \to\infty$), but this kind of limit does not explain why the old theory was successful. As a matter of fact, c is constant and the *actual* success of the old theory cannot be accounted for in terms of solutions that converge only under *counterfactual* circumstances (Rohrlich 1988). For limit-case reduction to explain the success of the old theory and yield the coherence in question, the limits have to be specified in terms of parameters that can take different values in the actual world, such as v/c.
2. Limit processes presuppose a "topological stage" (Scheibe 1997). A choice of topology is required to define the limit because it assumes a concept of convergence. This choice could be nontrivial, and whether or not a pair of solutions counts as similar may depend on it. Some recent work focuses on developing criteria for this choice (Fletcher 2015).
3. Limit processes may involve idealizations. The "thermodynamic limit" assumes that the number of particles in a system goes to infinity. This issue has been discussed extensively with respect to phase-transitions and critical phenomena (Batterman 2000, 2002, 2011, Butterfield 2011, Morrison 2012, Norton 2012, Menon and Callender 2013).

> Thermodynamics typically describes systems in terms of macroscopic quantities, which often depend only on other macroscopic quantities, not the microphysical details. From the perspective of statistical mechanics, this can be explained only in the thermodynamic limit (i.e., for systems with an infinite size) because it is only in this limit that the sensitivity to microphysical details disappears. Explaining the nonfluctuating quantities in terms of infinite system size is an idealization because real systems have only finitely many constituents. However, this is unproblematic if one can approach the limit smoothly; that is, neighbouring solutions for large yet finite systems differ minimally from solutions in the thermodynamic limit. Thus, in this case, statistical mechanics can explain why thermodynamic descriptions apply to large systems—the appeal to infinity is eliminable (Hüttemann et al. 2015).

Other cases may be more problematic for limit-case reduction. Thermodynamically, phase transitions and critical phenomena are associated with non-analyticities in a system's thermodynamic functions (i.e., discontinuous changes in a derivative of the thermodynamic function). Such non-analyticities cannot occur in *finite* systems as described by statistical mechanics because it allows for phase transitions only in *infinite* particle systems (see, e.g., Menon and Callender 2013). It has been argued that if the limit is singular, then solutions in the limit differ significantly from the neighboring (i.e., finite-system) solutions, and these fail to display phase transitions. Thus the appeal to infinity appears to be ineliminable for the explanation of the observed phase transitions (Batterman 2011), though this claim has been disputed (Butterfield 2011, Norton 2012, Menon and Callender 2013). The question then is: Under what conditions does the appeal to (infinite) idealizations undermine limit-case reduction? Disagreement partially depends on the conditions that successful reductions are supposed to fulfill. Does it suffice for the new theory to explain *the success* of the old theory, or should it explain the old theory itself, which may require the logical deduction of the equations of the old theory (Menon and Callender 2013)?

3.3. Reductive Explanations in Physics

It is sometimes argued that quantum mechanics and quantum entanglement in particular tell us that, "reductionism is dead . . . the total physical state of the joint system cannot be regarded as a consequence of the states of its (spatially separated) parts, where the states of the parts can be specified without reference to the whole" (Maudlin 1998, 54). This claim concerns neither Nagelian reduction nor limit-case reduction because it is not about pairs of theories. The claim is rather that, within one and the same theory (i.e., quantum mechanics), the state of the compound system cannot be explained in terms of the states of the parts. Maudlin's anti-reductionist claim does not concern the failure of a particular theory reduction but rather the failure of a kind of part-whole explanation.

In contrast to philosophy of biology (see Section 4), part-whole explanations have not been discussed in detail within philosophy of physics. One attempt to characterize part-whole explanations in physical science follows suggestions made by C. D. Broad (1925). According to this conception, a compound (whole) system's behavior can be explained by its parts if it can be explained in terms of (a) general laws concerning the behavior of the components considered in isolation, (b) general laws of composition, and, (c) general laws of interaction. Many macroscopic features like specific heat and the thermal or electrical conductivity of metals or crystals can be explained according to this model (Hüttemann 2004, 2005). Quantum entanglement is perhaps the most interesting case because the reductive explanation of the whole in terms of its parts clearly fails (Humphreys 1997, Hüttemann 2005, Maudlin 1998).

4. Biology

4.1. From Nagelian Theory Reduction to an Antireductionist Consensus

Historically, discussions of reductionism in the life sciences included extended arguments about vitalism, the claim that nonphysical or nonchemical forces govern biological systems. The story is more complex than a bald denial of physicalism, in part because what counts as "physicalism" and "vitalism" differ among authors and over time. Some late-eighteenth-century authors took a vitalist position that appealed to distinctly biological (i.e., natural) forces on analogy with NM, whereas organicists of the early twentieth century focused on organization as a nonreducible, system-level property of organisms. Many questions in the orbit of vitalism are reflected in contemporary discussions, but here we concentrate on how different aspects of reduction gained traction when the molecularization of genetics was juxtaposed with a revised form of Nagelian theory reduction. The manifold difficulties encountered in applying theory reduction to the relationship between classical and molecular genetics encouraged new approaches to explanatory reduction that were forged on a wide variety of biological examples where theories were much less prominent, especially within the ambit of different approaches to scientific explanation (e.g., mechanism descriptions).

A central motivation for Schaffner's refinement of the Nagelian model (see Section 2) was the putative success of molecular biology in reducing aspects of traditional fields of experimental biology to biochemistry. Although this was a work in progress, it was assumed that a logical derivation of classical genetics from a finished theory of biochemistry was in principle possible and would eventually be achieved. Schaffner's account and the case of genetics was the touchstone of discussions about reduction in philosophy of biology for several decades. Most of the reaction was critical, spawning an "antireductionist consensus." Three core objections were leveled against Schaffner's GRM:

1. Molecular genetics appeared to be replacing classical genetics, which implied that the reductive relations among their representations were moot (Ruse 1971, Hull 1974). A suitably corrected version of the higher-level theory seemingly yields a different theory that has replaced classical genetics in an organic, theory-revision process (Wimsatt 2007, ch. 11).
2. Nagel and Schaffner assumed that a theory is a set of statements in a formal language with a small set of universal laws (Kitcher 1984). The knowledge of molecular genetics does not correspond to this type of theory structure, which called into question the presumed logical derivation required to accomplish a reduction (Culp and Kitcher 1989, Sarkar 1998).
3. GRM focused on formal considerations about reduction rather than substantive issues (Hull 1976, Sarkar 1998, Wimsatt 2007, ch. 11). This was made poignant in the acknowledgment that GRM was peripheral to the actual practice of molecular genetics (Schaffner 1974). If reduction is a logical relation between theories that is only "in principle" possible, why

should we think GRM captures the progressive success of molecular genetics in relation to classical genetics?[2]

4.2. Models of Explanatory Reduction

These three objections—the difference between reduction and replacement in the context of theories changing over time, the mismatch between GRM theory structure assumptions and the knowledge practices of geneticists, and the gap between in principle formal problems and in practice substantive issues—collectively spurred new approaches to reduction in biology that were more sensitive to case studies of knowledge development, more empirically adequate with respect to the actual reasoning practices observed, and more responsive to substantive issues about reduction in practice (Kaiser 2011). These models of *explanatory* reduction differ from theory reduction in at least two salient ways: (a) they permit a variety of features as relata in reductions, such as subsets of a theory, generalizations of varying scope, mechanisms, and individual facts; and (b) they foreground a feature absent from the discussion of GRM, the idea that a reduction explains the whole in terms of its parts (Winther 2011).

One model of explanatory reduction that was animated by all three objections and exemplifies different reductive relata is the difference-making principle—gene differences cause differences in phenotypes (Waters 1990, 1994, 2000). Waters identifies this as a central principle of inference in both classical genetics and molecular genetics. An explanatory reduction is achieved between them because the causal roles of genes in instantiations of the inference correspond in both areas of genetics. Another model—explanatory heteronomy—requires that the *explanans* include biochemical generalizations, but the *explanandum* can be generalizations of varying scope, mechanisms, and individual facts that make reference to higher-level structures, such as cells or anatomy (Weber 2005). One of the most prominent models of explanatory reduction to emerge in the wake of theory reduction is mechanistic explanation (Darden 2006, Craver 2007, Bechtel 2011, Bechtel and Abrahamsen 2005, Glennan 1996), but whether it should be categorized as explanatory reduction is unclear (see Section 4.3).

Many models of explanatory reduction focus on how a higher-level feature or whole is explained by the interaction of its lower-level constituent parts. These approaches stress the importance of decomposing complex wholes into interacting parts of a particular kind (Kauffman 1971, Bechtel and Richardson 1993, Wimsatt 2007, ch. 9, Sarkar 1998). There is no commitment to the wholes and parts corresponding to different sciences or theories in order to achieve a compositional redescription or causal explanation of a higher-level state of affairs in terms of its component features (Wimsatt 2007, ch. 11, Hüttemann and Love 2011). These models avoid the basic objections facing GRM and fit well with the absence of clearly delineated theories in genetics, the emphasis on a whole being explained in terms of its parts in molecular explanations, and the piecemeal nature of actual scientific research. Molecular biology can offer reductive explanations despite the fact that many details are left our or remain unexplained.

4.3. Mechanistic Explanation and Reduction

Although several philosophers drew attention to the fact that biologists use the language of “mechanism” regularly and emphasize explanation in terms of decomposing a system into parts and then describing how these parts interact to produce a phenomenon (Kauffman 1971, Wimsatt 2007, ch. 9, 11), this was largely ignored because the conception of explanation diverged from the predominant deductive-nomological framework (Hempel and Oppenheim 1965[1948]). Explanatory power derived from laws in this framework, and their absence from a mechanism description meant they were interpreted as either temporary epistemic formulations or, to the degree that they were explanatory, reliant on “laws of working” (Glennan 1996, Schaffner 1993). These laws of working were presumed to be a part of a lower-level theory that would (in principle) reductively explain the features of higher-level entities.

One of the preeminent reasons offered for a mechanisms approach was its ubiquity in practice, both past and present (Darden 2006, Machamer, Darden, and Craver 2000). Reduction and replacement fail to capture the relations between classical and molecular genetics. These sciences deal with different mechanisms that occur at different points of time in the cell cycle—classical genetics focuses on meiosis, whereas molecular genetics focuses on gene expression—and involve different entities, such as chromosomal behavior for classical genetics and nucleotide sequences for molecular genetics. Mechanisms approaches share the values of sensitivity to actual knowledge development, empirical adequacy with respect to scientific practices, and awareness of substantive rather than formal issues. Discussions about mechanistic explanation derive from attention to large areas of successful science, especially molecular biology and neurobiology, where standard conceptions of theory structure, explanation, and reduction seem ill suited to capture actual scientific practices. In this sense, they are motivated by the mismatch between GRM theory structure assumptions and the knowledge practices of geneticists: “these models do not fit neuroscience and molecular biology” (Machamer et al. 2000, 23).

Should we understand mechanisms as a variant on explanatory reduction? In one sense, the answer is “no” because of a stress on the multilevel character of mechanism descriptions. Instead of logical relations between two theories or levels, the entire description of the mechanism, which involves entities and activities operating at different levels, is required.[3]

And yet almost all approaches to mechanistic explanation share the idea of explaining by decomposing systems into their constituent parts, localizing their characteristic activities, and articulating how they are organized to produce a particular effect. Mechanistic explanations illustrate and display the generation of specific phenomena by describing the organization of a system’s constituent components and activities. Additionally, entities and activities at different levels bear the explanatory weight unequally, and it becomes important to look at abstraction and idealization practices involved in representing mechanisms (Brigandt 2013b, Levy and Bechtel 2013, Love and Nathan forthcoming). These show patterns of reasoning where some kinds of entities and activities are taken to be more explanatory than others. To the degree that these are lower-level features, a form of explanatory reduction may be occurring. Discussions of “bottoming out” are germane to sorting out this possibility. The existence of “components that are accepted as relatively fundamental” (Machamer et al. 2000, 13) provides a clear rationale for why biologists often label mechanistic descriptions as reductive. That one science takes restricted types of entities or activities as fundamental, and another science takes different types of entities or activities as fundamental, does not mean reduction is inapplicable.

Whether mechanistic explanation circumvents discussions of explanatory reduction is an open question (Craver 2005). A core reason for the difficulty in answering the question is that mechanisms approaches are sometimes advanced as a package deal; they not only avoid reduction*ism* but also provide a novel conception of how knowledge is structured and account for how scientific discovery operates. But once a shift has been made from theory reduction to explanatory reduction, many of the issues comprising Schaffner's GRM package become disaggregated. The crucial issue becomes characterizing reduction so as to better identify what assumptions are and are not being made about associated issues, such as theory structure or explanation (Sarkar 1998).

4.4 Standard Objections to Models of Theory and Explanatory Reduction

Although Schaffner's GRM faced a variety of specific objections, there are two standard objections to both theory and explanatory reduction that routinely arise: (a) context: the effects of lower-level entities and their interactions depend on the context in which they occur, which leads to one-many relations between lower-level features and higher-level features; and (b) multiple realization: higher-level features can be implemented by different kinds of lower-level features, so that many-one relations between lower-level features and higher-level features obtain. We cannot do justice to the complexity of these standard objections, but it is important to describe their main contours (see Brigandt and Love 2012).

Classical geneticists were aware of the fact that a phenotype is brought about by the interaction of several classical genes—the same allele may lead to two different phenotypes if occurring in two individuals with a different genotype (Waters 2004).

There are many situations where the relationship between lower-level features and higher-level features is context dependent (Gilbert and Sarkar 2000, Hull 1974, Wimsatt 1979, Burian 2004). These different contexts include the developmental history, spatial region, and physiological state of a cell or organism. Reduction seems to fail because there is a one-many relation between lower-level and higher-level features, both compositionally and causally. The context of the organized whole is somehow primary in understanding the nature and behavior of its constituent parts.

Proponents of theory reduction have replied that a molecular reduction can take the relations of parts and the context of lower-level features into account. For example, one could specify the relevant context as initial conditions so that the higher-level features can be deduced in conjunction with premises about lower-level features. This strategy is subject to an objection plaguing Schaffner's GRM—scientists simply do not do this. The logical derivation of theory reduction would require that a representation of higher-level features be deduced from premises containing any and all of the lower-level context (internal or external) that is causally relevant. This may be possible in principle but not in practice. Models of explanatory reduction avoid this concern entirely. Explanations can highlight one among many causes, relegating everything else to the background, which is often held fixed in experimental studies. Explanations can appeal to a gene as a salient causal factor relative to a context even if the other genes involved in the phenotype are unknown and the cellular context of the gene has not yet been understood (Waters 2007). If biologists discover that the same mechanism produces different effects in distinct contexts, and only one of these effects is the target of inquiry, then the relevant aspects of the context can be included (Delehanty 2005). In this respect, models of explanatory reduction have a clear advantage over models of theory reduction.

Turning to multiple realization, the fact that higher-level features can be implemented by different kinds of lower-level features (many-one relations) also seems to challenge reductions. Knowledge of the lower-level features alone is somehow inadequate to account for the higher-level feature. For example, higher-level wholes can be composed of different lower-level component configurations or produced through causal processes that involve different interactions among lower-level components (Brigandt 2013a). Schaffner defends GRM against this objection by emphasizing that it is sufficient to specify one such configuration of lower-level features from which the higher-level feature can be derived (Schaffner 1976). This reply is inadequate because scientists usually attempt to explain types of higher-level phenomena rather than tokens; for example, not *this* instantiation of classical genetic dominance in pea plants but classical genetic dominance in sexually reproducing multicellular organisms. Token-token reduction may be possible but is relatively trivial epistemologically, whereas type-type theory reduction is empirically false due to multiple realization (Fodor 1974, 1997, Kimbrough 1978).

One inference that has been drawn from this result is that higher-level theories are justified in abstracting away from irrelevant variation in lower-level features to arrive at explanatory generalizations that involve natural kinds at higher levels (Kitcher 1984, Strevens 2009), though lower-level features may be informative for exceptions to a higher-level generalization. Models of explanatory reduction must deal with many-one relations between lower-level features and higher-level features, but it is a potentially manageable problem. One mitigation strategy is to challenge the commitment to unification that implies there is an explanatory loss in appealing to the multiply realized "gory details" (Waters 1990). Scientists find explanations of higher-level phenomena in terms of disjunctive lower-level types preferable in many cases. More generally, scrutinizing this lower-level heterogeneity facilitates a fine-grained dissection of compositional and causal differences that are otherwise inexplicable at the higher-level (Sober 1999). Thus models of explanatory reduction can manage multiple realizability objections through an emphasis on different explanatory virtues. Sometimes a lower-level explanation is better relative to one virtue (e.g., specificity), while a higher level explanation is preferable relative to another (e.g., generality).

4.5 Case Studies: Molecular, Developmental, and Behavioral Biology

Despite the emphasis on the relationship between classical and molecular genetics, philosophers of biology have analyzed reduction in other domains, such as evolutionary biology (Beatty 1990, Dupré 1993, Rosenberg 2006, Okasha 2006). Three brief examples from molecular, developmental, and behavioral biology are valuable in surfacing further conceptual issues relevant to models of explanatory reduction.

All models of explanatory reduction require representing the phenomena under investigation, just not always in terms of a theory (Sarkar 1998). Mathematical equations, scale miniatures, and abstract pictorial diagrams are examples. Every epistemological reduction involves a representation of the systems or domains to be related. Discussions surrounding the standard objections of one-many and many-one relationships in biological systems largely ignore questions related to representation, such as idealization or approximation, even though these have an impact on arguments about reduction. For example, hierarchical levels ("higher" and "lower") can be represented in different ways. Questions of one-many or many-one relations between different levels can be answered differently depending on how a hierarchy is represented (Love 2012). The decomposition of a system into parts depends on the principles utilized, such as function versus structure, and these can yield competing and complementary sets of part representations for the same system (Kauffman 1971, Wimsatt 2007, ch. 9, Bechtel and Richardson 1993, Winther 2011). Therefore, questions of representational choice and adequacy need to be addressed prior to determinations of whether reductive explanations succeed or fail. One can have successful reductions of features of complex wholes to constituent parts under some representations and simultaneously have failures of reduction under different representations, a situation that scientists methodologically exploit for the purpose of causal discovery (Wimsatt 2007, ch. 12).

In addition to hierarchy, another representational issue salient in biological explanations is temporality (Hüttemann and Love 2011). In most discussions of explanatory reduction, no explicit distinction has been drawn between compositional or spatial relations (arrangements) and causal or temporal relations (dynamics). Spatial composition questions have dominated, but biological models are frequently temporal if not explicitly causal (Schaffner 1993).[4] This is because a key aim is to explain how the organizational relations between parts change over time. Scientific explanations commonly invoke dynamic (causal) processes involving entities on several levels of organization (Craver and Bechtel 2007). Temporality takes on special significance in developing organisms where interactions over time among parts bring about new parts and new interactions (Parkkinen 2014). An orientation toward compositional reduction has encouraged an assumption of no change in the constituency of a whole being related to its parts.

Protein folding within molecular biology illustrates the importance of temporality (Love and Hüttemann 2011, Hüttemann and Love 2011). Functional proteins are folded structures composed of amino acid components linked together in a linear chain. If we ask whether the folded protein is mereologically composed of its amino acid parts given current representations in molecular biology, then we get an affirmative answer for an explanatory reduction with respect to composition. But if we ask whether the linear amino acid chain folds into a functional protein (a causal process with a temporal dimension) purely as consequence of its linked amino acid parts, then the answer is less clear. Empirical studies have demonstrated that other folded proteins (i.e., wholes) are required to assist in the proper folding of newly generated linear amino acid chains (Frydman 2001). The significance of temporality and dynamics is foregrounded precisely because the linked amino acid components alone are sufficient constitutionally but insufficient causally (Mitchell 2009), and the relations concern only molecular biological phenomena (as opposed to higher levels of organization, such as cells or anatomy).

Once the distinction between composition and causation is drawn, another issue related to representation becomes visible: reductive causal explanations that involve appeals to more than one type of lower-level feature (Love 2015, forthcoming). Explanations in developmental biology can be interpreted as reductive with respect to the difference-making principle (Waters 2007). Genetic explanations identify changes in the expression of genes and interactions among their RNA and protein products that lead to changes in the properties of morphological features during ontogeny (e.g., shape or size), while holding a variety of contextual variables fixed. Another type of reductive explanation invokes mechanical forces due to the geometrical arrangements of mesoscale materials, such as fluid flow (Forgacs and Newman 2005), which also can be interpreted as ontogenetic difference makers. Instead of preferring one reductive explanation to another or viewing them as competitors, many biologists seek to represent the combined dynamic of both types of lower-level features to reductively explain the manifestation of higher-level features of morphology: "an increasing number of examples point to the existence of a reciprocal interplay between expression of some developmental genes and the mechanical forces that are associated with morphogenetic movements" (Brouzés and Farge 2004, 372, Miller and Davidson 2013).

Finding philosophical models for the explanatory integration of genetics and physics is an ongoing task, but the ability to represent these causal relations in temporal periodizations is a key element of explanatory practice (Love forthcoming). This type of situation was not recognized in earlier discussions because reduction was conceptualized in terms of composition rather than causation and as a two-place relation with a single, fundamental lower level. A reductive explanation of a higher-level feature in terms of two different kinds of lower-level features was unimagined (and ruled out) within theory reduction because of the layer-cake view of theories corresponding to distinct levels of organization. It was ignored in most models of explanatory reduction, which focused on dyadic relations between classical genetics and molecular genetics or morphology and molecules.

The possibility of reductive explanations involving both molecular genetics and physics is a reminder that we routinely observe the coordination of a multiplicity of approaches, some reductive and others not, in biological science. An illuminating example is the study of human behavioral attributes such as aggression and sexuality (Longino 2013). Several different approaches to these behaviors can be distinguished, such as quantitative behavioral genetics, social-environmental analysis, molecular behavioral genetics, and neurobiology. Some of these are reductive in the sense of identifying lower-level features (e.g., genetic differences) to account for higher-level features (i.e., behavioral differences); others are not (e.g., social-environmental differences). Reductive relationships exist among the approaches themselves, such as the relationship between quantitative behavioral genetics and molecular behavioral genetics. When examined closely, Longino shows that different approaches conceptualize the higher-level phenomenon of behavior differently (e.g., patterns of individual behavior or tendencies in a population) and parse the space of causal possibilities differently (e.g., allele pairs, neurotransmitter metabolism, brain structure, and parental income). Each approach, reductive or otherwise, is limited; there is no fundamental level in the science of behavior and no single hierarchy of parts and wholes in which to organize the approaches.[5] There can be multiple successes and failures of different kinds of reductive explanation within the study of aggression and sexuality, but these arise from different representational assumptions and explanatory standards—multiple concepts of reduction are required simultaneously.

5. Conclusion

A major theme emerging from the previous discussion is that the epistemological heterogeneity and patchwork organization of the natural sciences requires an array of concepts to capture the diversity of asymmetrical, reductive relations found in the sciences, in addition to symmetrical, coordinative relations. This theme has been tracked in the growing specialization within philosophy of science, but it also has nurtured a growing rift between metaphysical questions about reductionism and epistemological questions about reduction. The "in practice" successes or failures of particular explanatory reductions do not yield straightforward building blocks for various projects in metaphysics that frequently demand more universal claims about the existence, availability, or desirability of reductions (i.e., forms of reductionism). A shift toward in practice considerations does not mesh tightly with metaphysical projects, such as deciding whether a higher-level feature is emergent and not reducible, and therefore the significance of debates about mechanistic explanation and models of explanatory reduction may appear irrelevant to topics of discussion in philosophy of mind or metaphysics.

We offer a procedural recommendation by way of a conclusion: given the existence of many senses of reduction that do not have straightforward interrelations, terminology such as "reductionist versus anti-reductionist" should be avoided. It is more perspicuous to articulate particular metaphysical and epistemological notions of reduction and then define acceptance or rejection of those notions or their failure or success in specific areas of science. This means it will be possible to argue for the success and failure of different types of reduction simultaneously within a domain of inquiry (Hüttemann and Love 2011). There is a strong rationale for talking about different kinds of reduction rather than in terms of a unified account of reduction or overarching dichotomies of reductionism versus anti-reductionism. Once we incorporate distinctions regarding different types of epistemological reduction (e.g., Nagel reduction, limit-case reduction, and part-whole reduction), the different interpretations of these types (e.g., the difference-making principle versus mechanisms as types of explanatory reduction), the different kinds of explanatory virtues that operate as standards (e.g., logical derivation, specificity, and generality), and the different kinds of representational features involved (spatial composition, causal relationships, or temporal organization), it is problematic to seek a single conception of reduction that will do justice to the diversity of phenomena and reasoning practices in the sciences. No global notion of reduction accurately characterizes what has occurred in the past or is currently happening in all areas of scientific inquiry. A pluralist stance toward reduction seems warranted (Kellert et al. 2006).

Acknowledgments

Order of authorship is alphabetical. Andreas Hüttemann is supported in part by funding from the Deutsche Forschungsgemeinschaft (Research Group: Causation and Explanation [FOR 1063]). Alan Love is supported in part by a grant from the John Templeton Foundation (Integrating Generic and Genetic Explanations of Biological Phenomena, ID 46919). We would like to thank Paul Humphreys and Samuel Fletcher for helpful comments.

References

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

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

Batterman, R. W. (2000). “Multiple Realizability and Universality.” *The British Journal for Philosophy of Science* 51:115–145.

Batterman, R. W. (2002). *The Devil in the Details: Asymptotic Reasoning in Explanation, Reduction, and Emergence* (Oxford: Oxford University Press).

Batterman, R. W. (2011). “Emergence, Singularities, and Symmetry Breaking.” *Foundations of Physics* 41:1031–1050.

Beatty, J. (1990). “Evolutionary Anti-Reductionism: Historical Reflections.” *Biology and Philosophy* 5:197–210.

Bechtel, W. (2011). “Mechanism and Biological Explanation.” *Philosophy of Science* 78:533–557.

Bechtel, W., and Abrahamsen, A. (2005). “Explanation: A Mechanist Alternative.” *Studies in the History and Philosophy of Biology and Biomedical Sciences* 36:421–441.

Bechtel, W., and Richardson, R. (1993). *Discovering Complexity: Decomposition and Localization as Strategies in Scientific Research* (Princeton, NJ: Princeton University Press).

Brigandt, I. (2013a). “Explanation in Biology: Reduction, Pluralism, and Explanatory Aims.” *Science & Education* 22:69–91.

Brigandt, I. (2013b). “Systems Biology and the Integration of Mechanistic Explanation and Mathematical Explanation.” *Studies in History and Philosophy of Biological and Biomedical Sciences* 44:477–492.

Brigandt, I., and Love, A. C. (2012). "Reductionism in Biology." In E. N. Zalta (ed.), *Stanford Encyclopedia of Philosophy,* http://plato.stanford.edu/entries/reduction-biology/.

Broad, C. D. (1925). *Mind and its Place in Nature*.(London: Routledge & Kegan Paul).

Brouzés, E., and Farge, E. (2004). "Interplay of Mechanical Deformation and Patterned Gene Expression in Developing Embryos." *Current Opinion in Genetics & Development* 14:367–374.

Burian, R. M. (2004). "Molecular Epigenesis, Molecular Pleiotropy, and Molecular Gene Definitions." *History and Philosophy of the Life Sciences* 26:59–80.

Butterfield, J. (2011). "Less Is Different: Emergence and Reduction Reconciled." *Foundations of Physics* 41:1065–1135.

Chalmers, D. (1996). *The Conscious Mind: In Search of a Fundamental Theory* (New York: Oxford University Press).

Craver, C. F. (2005). "Beyond Reduction: Mechanisms, Multifield Integration and the Unity of Neuroscience." *Studies in the History and Philosophy of Biological and Biomedical Sciences* 36:373–395.

Craver, C. F. (2007). *Explaining the Brain: Mechanisms and the Mosaic Unity of Neuroscience* (New York: Oxford University Press).

Craver, C. F., and Bechtel, W. (2007). "Top-Down Causation Without Top-Down Causes." *Biology & Philosophy* 22:547–563.

Culp, S., and Kitcher, P. (1989). "Theory Structure and Theory Change in Contemporary Molecular Biology." *The British Journal for the Philosophy of Science* 40:459–483.

Darden, L. (2006). *Reasoning in Biological Discoveries: Essays on Mechanisms, Interfield Relations, and Anomaly Resolution* (New York: Cambridge University Press).

Delehanty, M. (2005). "Emergent Properties and the Context Objection to Reduction." *Biology & Philosophy* 20:715–734.

Dizadji-Bahmani, F., Frigg, R., and Hartmann, S. (2010). "Who's Afraid of Nagelian Reduction?" *Erkenntnis* 73:393–412.

Dupré, J. (1993). *The Disorder of Things: Metaphysical Foundations of the Disunity of Science* (Cambridge, MA: Harvard University Press).

Earman, J. (1989). *World Enough and Spacetime: Absolute versus Relational Theories of Space and Time* (Cambridge, MA: MIT Press).

Ehlers, J. (1986). "On Limit Relations Between and Approximate Explanations of Physical Theories." In B. Marcus, G. J. W. Dorn, and P. Weingartner (eds.), *Logic, Methodology and Philosophy of Science, VII* (Amsterdam: Elsevier), 387–403.

Ehlers, J. (1997). "Examples of Newtonian Limits of Relativistic Spacetimes." *Classical and Quantum Gravity* 14:A119–A126.

Feyerabend, P. K. (1962). "Explanation, Reduction and Empiricism." In H. Feigl and G. Maxwell (eds.), *Scientific Explanation, Space, and Time* (Minneapolis: University of Minnesota Press), 28–97.

Fletcher, S. (2015). "Similarity, Topology, and Physical Significance in Relativity Theory." *The British Journal for the Philosophy of Science*. doi: 10.1093/bjps/axu044

Fodor, J. A. (1974). “Special Sciences (Or: the Disunity of Sciences as a Working Hypothesis).” *Synthese* 28:77–115.

Fodor, J. A. (1997). “Special Sciences: Still Autonomous After All These Years.” In J.A. Tomberlin (ed.), *Mind, Causation and World–Philosophical Perspectives,* Vol. 11 (Oxford: Blackwell), 149–163.

Forgacs, G., and Newman, S. A. (2005). *Biological Physics of the Developing Embryo* (New York: Cambridge University Press).

Friedman, M. (1986). *Foundations of Space-Time Theories: Relativistic Physics and Philosophy of Science* (Princeton, NJ: Princeton University Press).

Frydman, J. (2001). “Folding of Newly Translated Proteins in Vivo: The Role of Molecular Chaperones.” *Annual Review of Biochemistry* 70:603–647.

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

Glennan, S. (1996). “Mechanisms and the Nature of Causation.” *Erkenntnis* 44:49–71.

Hempel, C. G., and Oppenheim, P. (1965 [1948]). “Studies in the Logic of Explanation.” In *Aspects of Scientific Explanation and other Essays in the Philosophy of Science* (New York: Free Press), 245–290.

Hendry, R., and Needham, P. (2007). “Le Poidevin on the Reduction of Chemistry.” *The British Journal for the Philosophy of Science* 58:339–353.

Hull, D. L. (1974). *Philosophy of Biological Science* (Englewood Cliffs, NJ: Prentice-Hall).

Hull, D. L. (1976). “Informal Aspects of Theory Reduction.” *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association 1974*:653–670.

Humphreys, P. (1997). "How Properties Emerge." *Philosophy of Science* 64:1–17.

Hüttemann, A. (2004). *What's Wrong with Microphysicalism?* (London: Routledge).

Hüttemann, A. (2005). "Explanation, Emergence, and Quantum Entanglement." *Philosophy of Science* 72:114–127.

Hüttemann, A., Kühn, R., and Terzidis, O. (2015). "Stability, Emergence and Part-Whole-Reduction." In *Why More Is Different: Philosophical Issues in Condensed Matter Physics and Complex Systems*, edited by, 169–200. Dordrecht: Springer.

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

Kaiser, M. I. (2011). "The Limits of Reductionism in the Life Sciences." *History and Philosophy of the Life Sciences* 33(4):453–476.

Kaiser, M. I. (2012). "Why It Is Time to Move beyond Nagelian Reduction." In D. Dieks, W.J. Gonzalez, S. Hartmann, M. Stöltzner, and M. Weber (eds.), *Probabilities, Laws, and Structures* (Berlin: Springer), 245–262.

Kauffman, S. A. (1971). "Articulation of Parts Explanations in Biology and the Rational Search for Them." *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association 1970*:257–272.

Kellert, S. H., Longino, H. E., and Waters, C. K. (2006). "Introduction: The Pluralist Stance." In S. H. Kellert, H. E. Longino and C. K. Waters (eds.), *Scientific Pluralism* (Minneapolis: University of Minnesota Press), vii–xxix.

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

Kim, J. (1998). *Mind in a Physical World* (Cambridge, MA: MIT Press).

Kim, J. (2005). *Physicalism, or Something Near Enough* (Princeton, NJ: Princeton University Press).

Kimbrough, S. O. (1978). “On the Reduction of Genetics to Molecular Biology.” *Philosophy of Science* 46:389–406.

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

Landsman, N. P. (2007). “Between Classical and Quantum.” In J. Earman and J. Butterfield (eds.), *Handbook of the Philosophy of Physics* (Amsterdam: Elsevier), 417–553.

Levine, J. (1993). “On Leaving Out What It’s Like.” In M. Davies and G. W. Humphreys (eds.), *Consciousness: Psychological and Philosophical Essays* (Oxford: Blackwell), 121–136.

Levy, A., and Bechtel, W. (2013). “Abstraction and the Organization of Mechanisms.” *Philosophy of Science* 80:241–61.

Longino, H. E. (2013). *Studying Human Behavior: How Scientists Investigate Aggression and Sexuality* (Chicago: University of Chicago Press).

Love, A. C. (2012). “Hierarchy, Causation and Explanation: Ubiquity, Locality and Pluralism. “ *Interface Focus* 2:115–125.

Love, A. C. (2015). “Developmental Biology.” In E. N. Zalta (ed.), *Stanford Encyclopedia of Philosophy*, http://plato.stanford.edu/entries/biology-developmental/.

Love, A. C. (forthcoming). “Combining Genetic and Physical Causation in Developmental Explanations.” In C. K. Waters and J. Woodward (eds.), *Causal Reasoning in Biology* (Minneapolis: University of Minnesota Press).

Love, A. C., and Hüttemann, A. (2011). “Comparing Part-Whole Reductive Explanations in Biology and Physics.” In D. Dieks, J. G. Wenceslao, S. Hartmann, T. Uebel, and M. Weber (eds.), *Explanation, Prediction, and Confirmation* (Berlin: Springer), 183–202.

Love, A. C., and Nathan, M. D. (forthcoming). “The Idealization of Causation in Mechanistic Explanation.” *Philosophy of Science*.

Machamer, P., Darden, L., and Craver, C. F. (2000). “Thinking about Mechanisms.” *Philosophy of Science* 67:1–25.

Maudlin, T. (1998). “Part and Whole in Quantum Mechanics.” In E. Castellani (ed.), *Interpreting Bodies* (Princeton, NJ: Princeton University Press), 46–60.

Menon, T., and Callender, C. (2013). “Turn and Face the Strange . . . Ch-ch-changes: Philosophical Questions Raised by Phase Transitions.” In R. Batterman (ed.), *The Oxford Handbook of Philosophy of Physics* (Oxford: Oxford University Press), 189–223.

Miller, C. J., and Davidson, L. A. (2013). “The Interplay Between Cell Signalling and Mechanics in Developmental Processes.” *Nature Reviews Genetics* 14:733–744.

Mitchell, S. D. (2009). *Unsimple Truths: Science, Complexity, and Policy* (Chicago and London: University of Chicago Press).

Morrison, M. (2012). “Emergent Physics and Micro-Ontology.” *Philosophy of Science* 79:141–166.

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

Nickles, T. (1973). "Two Concepts of Intertheoretic Reduction." *Journal of Philosophy* 70:181–201.

Norton, J. (2012). "Approximation and Idealization: Why the Difference Matters." *Philosophy of Science* 79:207–232.

Okasha, S. (2006). *Evolution and the Levels of Selection* (New York: Oxford University Press).

Oppenheim, P., and Putnam, H. (1958). "Unity of Science as a Working Hypothesis." In H. Feigl, M. Scriven, and G. Maxwell (eds.) *Concepts, Theories, and the Mind-Body Problem* (Minneapolis: University of Minnesota Press), 3–36.

Parkkinen, V-P. (2014). "Developmental Explanations." In M. C. Galavotti, D. Dieks, W. J. Gonzalez, S. Hartmann, T. Uebel, and M. Weber (eds.), *New Directions in the Philosophy of Science: The Philosophy of Science in a European Perspective,* Vol. 5 (Berlin: Springer), 157–172.

Rohrlich, F. (1988). "Pluralistic Ontology and Theory Reduction in the Physical Sciences." *The British Journal for the Philosophy of Science* 39:295–312.

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

Ruse, M. (1971). "Reduction, Replacement, and Molecular Biology." *Dialectica* 25:39–72.

Sarkar, S. (1992). "Models of Reduction and Categories of Reductionism." *Synthese* 91:167–94.

Sarkar, S. (1998). *Genetics and Reductionism* (Cambridge, UK: Cambridge University Press).

Schaffner, K. F. (1967). “Approaches to Reduction.” *Philosophy of Science* 34:137–47.

Schaffner, K. F. (1969). “The Watson-Crick Model and Reductionism.” *The British Journal for the Philosophy of Science* 20:325–48.

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

Schaffner, K. F. (1976). “Reductionism in Biology: Prospects and Problems.” *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association 1974*:613–632.

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

Scheibe, E. (1997). *Die Reduktion Physikalischer Theorien: Teil I, Grundlagen und Elementare Theorie* (Berlin: Springer).

Scheibe. E. (1999). *Die Reduktion Physikalischer Theorien: Teil II, Inkommensurabilitat und Grenzfallreduktion* (Berlin: Springer).

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

Sklar, L. (1993). *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (New York: Cambridge University Press).

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

Strevens, M. (2009). *Depth: An Account of Scientific Explanation* (Cambridge, MA: Harvard University Press).

Suppe, F., ed. (1977). *The Structure of Scientific Theories,* 2nd ed. (Urbana: University of Illinois Press).

Uffink, J. (2007). "Compendium of the Foundations of Classical Statistical Physics." In J. Earman and J. Butterfield (eds.), *Handbook of the Philosophy of Physics* (Amsterdam: Elsevier), 923–1074.

Waters, C. K. (1990). "Why the Antireductionist Consensus Won't Survive the Case of Classical Mendelian Genetics." *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association,* Vol. 1: Contributed Papers: 125–139.

Waters, C. K. (1994). "Genes Made Molecular." *Philosophy of Science* 61:163–185.

Waters, C. K. (2000). "Molecules Made Biological." *Revue Internationale de Philosophie* 4:539–564.

Waters, C. K. (2004). "What Was Classical Genetics?" *Studies in the History and Philosophy of Science* 35:783–809.

Waters, C. K. (2007). "Causes that Make a Difference." *Journal of Philosophy* 104:551–579.

Weber, M. (2005). *Philosophy of Experimental Biology* (New York: Cambridge University Press).

Weisberg, M., Needham, P., and Hendry, R. (2011). "Philosophy of Chemistry." In E. N. Zalta (ed.), *Stanford Encyclopedia of Philosophy*, http://plato.stanford.edu/entries/chemistry/.

Wimsatt, W. C. (1979). "Reductionism and Reduction." In P. D. Asquith and H. E. Kyburg (eds.), *Current Research in Philosophy of Science* (East Lansing, MI: Philosophy of Science Association), 352–377.

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

Winther, R. G. (2009). "Schaffner's Model of Theory Reduction: Critique and Reconstruction." *Philosophy of Science* 76:119–142.

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

Woodward, J. (2011). "Scientific Explanation." In E. N. Zalta (ed.), *Stanford Encyclopedia of Philosophy,* http://plato.stanford.edu/archives/win2011/entries/scientific-explanation/.

Figure 1

Kinetic energy as a function of the velocity of a particle relative to some observer (measured in *v/c*), as predicted by Newtonian mechanics and the special theory of relativity.

---

[1] "[I]n the case of (N)M and STR it is more natural to say that the *more* general STR reduces to the *less* general (N)M in the limit of low velocities. Epitomizing this intertheoretic reduction is the reduction of the Einsteinian formula for momentum, $p = m_0v / \sqrt{(1 - (v/c)^2)}$, where m_0 is the rest mass, to the classical formula $p = m_0v$ in the limit as $v \rightarrow 0$" (Nickles 1973, 182).

[2] Other formal approaches to theory structure also failed to capture the actual practices of scientific reasoning in genetics, thereby running afoul of the latter two objections (Balzer and Dawe 1986a, 1986b).

[3] "Higher-level entities and activities are . . . essential to the intelligibility of those at lower levels, just as much as those at lower levels are essential for understanding those at higher levels. It is the integration of different levels into productive relations that renders the phenomenon intelligible and thereby explains it" (Machamer et al. 2000, 23).

[4] A very different distinction utilizing time separates the historical succession of theories via reduction—diachronic reduction—from attempts to relate parts to wholes, such as in explanatory reduction or interlevel theory reduction —synchronic reduction (Rosenberg 2006, Dupré 1993).

[5] "Each approach offers partial knowledge of behavioral processes gleaned by application of its investigative tools. In applying these tools, the overall domain is parsed so that effects and their potential causes are represented in incommensurable ways. We can (and do) know a great deal, but what we know is not expressible in one single theoretical framework" (Longino 2013, 144).