Introduction

There are many important questions that do not fall neatly into any one discipline; rather, their full investigation requires the integration of two or more distinct fields. This book is about just such a question – one that arises at the intersection of physics, philosophy, and history. The question can be simply stated as "What is the relation between classical and quantum mechanics?" The simplicity of the question, however, belies the complexity of the answer. Classical mechanics and quantum mechanics are two of the most successful scientific theories ever developed, and yet how these two very different theories can successfully describe one and the same world – the world we live in – is far from clear. One theory is deterministic, the other indeterministic; one theory describes a world in which chaotic behavior is pervasive, and the other a world in which it is almost entirely absent. Did quantum mechanics simply replace classical mechanics as the new universal theory? Do they each describe their own distinct domains of phenomena? Or is one theory really just a continuation of the other?

In the philosophy literature, this sort of issue is known as the problem of intertheoretic relations.[1] Currently, there are two accepted philosophical frameworks for thinking about intertheoric relations: the first is reductionism, and the second, pluralism. As we shall see, these labels each actually describe a family of related views. Reductionism is roughly the view that one theory can be derived from another, either by means of a logical deduction or the mathematical limit of some parameter. Theoretical pluralism, by contrast, takes each scientific theory to have its own distinct domain of laws, entities, and concepts, which cannot be reduced to those of any other theory. The central thesis of this book is that neither reductionism nor pluralism adequately describes the relation between quantum and classical mechanics.

[1] In the philosophical literature, as in the remainder of this book, the terms 'intertheoretic' and 'intertheory' are used interchangeably.

In searching for a new philosophical framework for thinking about intertheory relations, I turn to the history of science, and examine the philosophical views of three of the founders of quantum theory: Werner Heisenberg, Paul Dirac, and Niels Bohr. Perhaps surprisingly, all three of these figures accorded to classical mechanics a role of continued *theoretical* importance; none of them took classical mechanics to be a discarded theory, rendered useless for all but "engineering" purposes. Moreover, I shall argue that none of them took the relation between classical and quantum mechanics to be captured by the usual reductionist account in terms of the classical limit ($\hbar \to 0$). Despite these two important similarities, however, all three of them held a very different view of the quantum–classical relation. As we shall see, Heisenberg's account of classical and quantum mechanics as "closed theories" led him to adopt a version of theoretical pluralism; Dirac, by contrast, saw a deep analogy or structural continuity between these theories; and Bohr viewed quantum theory as a "rational generalization" of classical mechanics. I shall show that not only do these historical views have many interesting parallels with contemporary debates in the philosophy of science, but they can also suggest new ways in which our present-day debates might be moved forward.

The question of the relation between classical and quantum mechanics cannot be decided on purely historical or philosophical grounds, but also requires delving into contemporary research in physics. I shall focus on an area of scientific research known as semiclassical mechanics. Very roughly, semiclassical mechanics can be thought of as the study of "mesoscopic" systems that are in the overlap between the classically described macroworld and the quantum mechanically described microworld. As such, it is a field ideally suited for exploring questions about the relationship between classical and quantum mechanics. More specifically, I shall focus on a subfield known as quantum chaos. The name "quantum chaos" is something of a misnomer, since quantum systems cannot exhibit the sort of sensitive dependence on initial conditions characteristic of classically chaotic behavior.[2] Instead, the field of quantum chaos is concerned with the study of quantum systems whose classical counterparts are chaotic. As we shall see, these quantum-chaotic systems pose a number of unique challenges for an adequate characterization of the quantum–classical relation. At the heart of this book is a summary of four areas of research in semiclassical mechanics that involve quantum systems whose classical counterparts are chaotic. These are the semiclassical solution of the helium atom, diamagnetic Rydberg atoms, wavefunction scarring, and quantum dots. These case studies will function as the "data" against which the adequacy of the philosophical accounts of intertheory relations will be tested.

[2] For a review of the reasons why there cannot typically be chaotic behavior in quantum systems see Bokulich (2001, p. x).

I shall argue that there are three surprising lessons to draw from this examination of semiclassical research: First, there is a variety of *quantum* phenomena ranging from atomic physics to condensed-matter physics, for which semiclassical mechanics – not pure quantum mechanics – provides the appropriate theoretical framework for investigating, calculating, and *explaining* these phenomena. Second, these semiclassical methods and explanations involve a thorough hybridization of classical and quantum ideas. Far from being incommensurable theoretical concepts, they can be combined in both empirically adequate and conceptually fruitful ways. Finally, the classical structures (such as periodic orbits) appealed to in semiclassical mechanics are not simply useful calculational devices, but are actually manifesting themselves in surprising ways in quantum *experiments* (that is, in ways that are not simply the quantum behavior mimicking the classical behavior). This speaks to a much richer continuity of dynamical structure across classical and quantum mechanics than is usually recognized.

These features of semiclassical research pose two important challenges for contemporary philosophy of science. First, the semiclassical appeals to classical structures in explaining quantum phenomena do not fit easily with either of the current orthodox accounts of scientific explanation (that is, they are neither deductive–nomological nor causal explanations). I shall argue that a new philosophical account of scientific explanation is called for and outline what such an account might look like.

Second, this semiclassical research also poses a challenge to the adequacy of our current philosophical frameworks for thinking about intertheory relations. More specifically, it reveals that an adequate account of the relation between classical and quantum mechanics should not just be concerned with the narrow (though of course important) question of how to recover classical behavior from quantum mechanics, but rather should recognize the many structural correspondences and continuities between the two theories. Of the three historical views that I examine, I shall argue that Dirac's "structural continuity" view provides the most adequate foundation for a new philosophical account of intertheory relations – one that can incorporate these insights from semiclassical research. This new view, which I call interstructuralism, takes from theoretical pluralism the insight that predecessor theories such as classical mechanics are still playing an important theoretical role in scientific research; that is, quantum mechanics – without classical mechanics – gives us an incomplete picture of our world. From reductionism, however, it takes the lesson that we cannot rest content with the view that each of these theories describes its own distinct domain of phenomena. We stand to miss out on many important scientific discoveries and insights if we do not try to bring our various theoretical descriptions of the world closer together.

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1

Intertheoretic relations: Are imperialism and isolationism our only options?

… that was to this, Hyperion to a satyr.

Shakespeare, Hamlet*, Act 1 Scene 2*

1.1 Introduction

The issue of intertheoretic relations is concerned with how our various theoretical descriptions of the world are supposed to fit together. As the physicist Sir Michael Berry describes it, "Our scientific understanding of the world is a patchwork of vast scope; it covers the intricate chemistry of life, the sociology of animal communities, the gigantic wheeling galaxies, and the dances of elusive elementary particles. But it is a patchwork nevertheless, and the different areas do not fit well together" (Berry 2001, p. 41). This uncomfortable patchwork exists even if we restrict our attention to within the field of physics alone. Physics itself consists of many subtheories, such as quantum field theory, quantum mechanics, condensed-matter theory, thermodynamics, classical mechanics, and the special and general theories of relativity – just to name a few. Each of these theories is taken to be an accurate description of some domain of phenomena, and insofar as they are supposed to be describing one and the same world, it is important to ask how these very different – and in many cases prima facie mutually inconsistent – theories are supposed to fit together.

Hitherto, the philosophical frameworks available for thinking about intertheory relations have been rather limited. Traditionally, discussions of intertheoretic relations have been framed in terms of reductionism.[1] The relationship between two scientific theories is taken to be either an accomplished, or an in-principle (though perhaps not in-practice) accomplishable, reduction of the higher-level (or predecessor)

[1] Throughout this book, the criticisms I raise against reductionism should be understood as being against *theory reductionism* or *explanatory reductionism*. At no point am I challenging ontological reductionism, or what philosophers sometimes call materialism. So, for example, I do not think that there are emergent properties that are not just the result of fundamental physical properties, their organization, and complex interactions.

theory to the lower-level (or successor) theory. On the reductionist picture, physics (or more precisely, high-energy physics) is the most fundamental and accurate description of the world, and the special sciences such as chemistry, biology, and psychology are merely incomplete shadows of – or approximations to – this more fundamental level of description. So on this view, for example, as biological theories become better and better, they should become more and more indistinguishable from theories in physics. Reductionism has furthermore been used as a justification for why more research funds should be invested in high-energy physics than in other areas of science, much to the vexation of scientists in other fields.[2]

In recent years, however, reductionism has increasingly fallen into disrepute. Reductionists are now likened to imperialists, who aim to illegitimately extend the power and dominion of a particular scientific theory by direct territorial acquisition. In place of reductionism, the new orthodoxy has become theoretical pluralism. Pluralists, by contrast, allot to each scientific theory its own circumscribed domain, not to be infringed upon by any of its neighbors. On this view, each of the special sciences has its own entities, laws, and descriptions, none of which are any less fundamental than the entities, laws and descriptions of physics. The theoretical pluralist Jerry Fodor, for example, titles his more recent (1997) defense of anti-reductionism "Special sciences: Still autonomous after all these years."[3]

In trying to avoid the reductionist's imperialism, however, the pluralists have adopted a position that is dangerously close to isolationism. In their renunciation of reductionism, theoretical pluralists have also renounced the important benefits that come from building strong and intimate ties with neighboring theories. Indeed it is arguably in trying to build bridges between these various different scientific domains that some of the most exciting new developments and discoveries are made.

In the following two sections I provide a brief overview of the various forms of reductionism and theoretical pluralism.[4] This will provide a useful framework for locating the alternative approaches to intertheoretic relations that I introduce in Chapters 2, 3, and 4. In Sections 1.4 and 1.5, I turn more specifically to the case of classical and quantum mechanics, and examine in some detail the most widely

[2] For example, Steven Weinberg in his chapter "Two Cheers for Reductionism" writes, "The reason we give the impression that we think that elementary particle physics is more fundamental than other branches of physics is because it is. I do not know how to defend the amounts being spent on particle physics without being frank about this" (Weinberg 1992, p. 55). In this book, Weinberg also briefly discusses how his views on reductionism have been challenged by the evolutionary biologist Ernst Mayr and the condensed-matter physicist Philip Anderson.

[3] While this paper is directed more specifically at Jaegwon Kim's reductionist arguments in psychology, it is a continuation of Fodor's (1974) arguments for the irreducibility and autonomy of the special sciences.

[4] Regrettably the brevity of this overview means I will be unable to do full justice to the subtleties of the various views summarized. As some compensation, I have tried to provide ample references for the interested reader to learn about these views in more depth.

received account of the relation between these theories, which is a form of reductionism. This will require a foray into contemporary research in physics that seeks to explain how quantum theory can recover (or reduce to) the everyday classical world we observe around us. The challenges raised there against the most widely received form of reductionism will be the first step in the argument, taken up again in Chapters 5, 6, and 7, that neither reductionism nor pluralism gives an adequate account of the relationship between classical and quantum mechanics.

1.2 Traditional accounts of reductionism

Part of the difficulty in deciding whether or not one theory is reducible to another is that there is no univocal understanding of what reductionism requires.[5] Reductionism can, for example, be construed as a thesis about ontologies, laws, theories, methodologies, or even linguistic expressions. Nor are these various construals of reductionism mutually exclusive. Furthermore, reductionism can be understood either as a synchronic relation – that is, a relation between two concurrent theories that belong to two different levels of description – or a diachronic relation describing the relation between a historical predecessor theory and its successor. This distinction between synchronic and diachronic reduction often becomes blurred in cases like classical and quantum mechanics, where the historical predecessor is a higher-level "macrotheory" and its successor is a "microtheory."

Reductionism is best thought of not as a single approach, but rather as a framework, or family of approaches. Different approaches to reductionism can be distinguished by the different ways in which the reductive relation is characterized. The three most prominent approaches to reductionism (which shall be briefly discussed in turn) are, first, Nagelian reductionism as logical deduction; second, Kemeny–Oppenheim reduction as an eliminative re-systematization; and finally, what is often called the "physicist's reductionism" as the asymptotic limit of some parameter.

The best-known formulation of reductionism in philosophy is that of Ernest Nagel. According to Nagel, "a reduction is effected when the experimental laws of the secondary science … are shown to be the logical consequences of the theoretical assumptions (inclusive of the coordinating definitions) of the primary science" (Nagel [1961] 1979, p. 352). Here, the secondary science is the predecessor theory (e.g., thermodynamics) and the primary science is the successor theory (e.g., statistical mechanics). Since reduction on this model is a logical derivation, there can be no term in the predecessor theory that is not in the successor theory. To overcome this difficulty, Nagel introduces the condition of connectability, which

5 For a taxonomy and discussion of various forms of reductionism see, for example, Sarkar (1992).

requires bridge principles or laws that would connect different terms in the two theories.

Critics quickly pointed out a number of theoretical problems with Nagel's model of reduction. For example, the required bridge laws can rarely be found, and the reduced theory requires assumptions that, in light of the new theory, are strictly speaking false.[6] More generally the conception of a scientific theory as a system of laws, on which Nagel's account of reductionism rests, has also been called into question. For example, it is not clear that theories in the special sciences, such as biology, have laws at all.[7] Most damaging, however, is the fact that no actual cases of intertheory relations have been able to fit Nagel's model.[8]

The second traditional philosophical approach to reductionism is due to John Kemeny and Paul Oppenheim. Partly in response to difficulties that they see in Nagel's account, they offer an alternative model of reductionism, which emphasizes simplicity and conceptual economy. According to Kemeny and Oppenheim, a scientific theory is nothing but a systematization of all of our observations to date. They write, "In place of an infinite set of observation statements we are given a reasonably simple theory. Such a theory has the same explanatory ability as the long (or infinite) list of statements, but no one will deny that it is vastly simpler and hence preferable to such a list. Only thus do we see the need for introducing theoretical terms" (Kemeny and Oppenheim 1956, p. 12). It is on this remarkably impoverished account of scientific theories that Kemeny and Oppenheim base their notion of reduction: A predecessor theory, T_2, is reduced to a successor theory, T_1, if all observational data that T_2 can explain is also explainable by T_1. To this they add the further condition that T_1 must be at least as well systematized as T_2, where "systematized" means "simpler" unless the loss of simplicity is counterbalanced by an increase in the strength or scope of the successor theory.

An important consequence of Kemeny and Oppenheim's account of reduction is that the predecessor theory, which is now nothing more than a superfluous systematization of observation statements, can simply be eliminated. Theory reduction, on this model more closely resembles theory replacement. Kemeny and Oppenheim note that while Nagel attempts to establish a direct relation between the two theories, "[our] connection is indirect … [O]f course, each set of theoretical terms must be connected to observational terms, and hence to each other, but this connection is normally much weaker than a full translation" (Kemeny and Oppenheim 1956,

[6] For an overview of some of these early objections to Nagel's model, as well as a defense of a neo-Nagelian model of reduction that attempts to overcome these objections, see Schaffner (1967).
[7] See, for example, Kitcher (1984).
[8] The literature on this topic is vast. For a sampling of challenges to Nagel's reduction in the context of specific theory pairs, see Fodor (1974) for psychology to neuroscience, Kitcher (1984) for classical Mendelian genetics to molecular biology, Scerri (1994) for chemistry to quantum mechanics, and Sklar (1999) for thermodynamics to statistical mechanics.

p. 16). If one abandons the idea that there is a fixed set of observation statements that is preserved in the move from one theory to another, as many post-positivist philosophers of science do, then even this indirect relation between the predecessor and successor theory is lost.

In addition to the deductive and eliminative models of theory reduction, there is a third general approach to intertheoretic reduction that is typically found in the physical sciences. Thomas Nickles labels this "reduction$_2$," which he notes is "best described by 'inverting' the usual concept of reduction, so that successors are said to reduce to their predecessors (not vice versa) under limiting operations" (Nickles 1973, p. 181). As Nickles notes, what amounts to a limiting operation can vary widely. Typically a parameter (or combination of parameters) is allowed to go to some limit. For example, it is commonly said that the special theory of relativity reduces$_2$ to Newtonian dynamics in the limit of small velocities (that is $v^2/c^2 \to 0$). In the context of classical and quantum mechanics, this third approach to reductionism is typically referred to as the "classical limit." Since this approach is by far the most widely received account of the relation between classical and quantum mechanics, it will be examined in some detail in Section 1.4. Before turning to physicists' characterizations of the classical limit, however, we shall briefly examine the chief rival to these traditional accounts of reductionism, namely, theoretical pluralism.

1.3 Theoretical pluralism

Like reductionism, theoretical pluralism is best thought of as not a single view, but rather a family of approaches. Theoretical pluralism, which is sometimes referred to as "scientific pluralism," has also been defended under the rubric of the "disunity of science." As a negative thesis, pluralism denies that the world is such that it can be explained by a single unified set of fundamental principles or laws.[9] The plurality of scientific theories describing different domains is neither a temporary feature of science, nor a permanent feature that is merely a consequence of our epistemic limitations as human knowers. Rather, there is some sense in which nature itself demands this plurality of descriptions; hence, any approach that seeks to reduce or eliminate this plurality is methodologically misguided and will result in a misrepresentation of nature.

Three different subspecies of theoretical pluralism can be distinguished: type-I theoretical pluralism, which defends the necessity of multiple

[9] Some versions of pluralism simply remain agnostic about this question, seeing this agnosticism as sufficient to undermine the normative claim that scientists *ought* to be seeking a unified account, and that the acceptability or maturity of a theory is, in large part, to be measured by the extent to which it achieves that unity. See, for example, Kellert, Longino, and Waters (2006).

scientific theories or models in describing *different* domains of phenomena; type-II, which defends a plurality of theories or models in describing the *same* (single) domain of phenomena; or type-III theoretical pluralism, which argues for both. Type-I theoretical pluralism is perhaps the most common, and is typically invoked to protect the autonomy of the special sciences. Challenges facing this version of theoretical pluralism include the problem of consistency that arises at the interface, or borderlands, between our various scientific theories. For the second and third types of pluralism, this problem of inconsistency is even more troubling, in so far as it is no longer confined to these borderlands, but rather pervades these theories. Even more troubling, however, is that these latter two types of theoretical pluralism threaten to lead to a relativism of "anything goes." Hence, those who want to embrace pluralism without relativism are faced with the challenge of articulating a set of constraints on which models and theories are to be counted among the scientifically legitimate ones for that domain of phenomena (Kellert *et al*. 2006, p. xiii).

Historically, the thesis of incommensurability played a central role in the move away from reductionism and towards theoretical pluralism. In responding to purported cases of reduction, such as the reduction of special relativity to Newtonian dynamics, both Thomas Kuhn ([1962] 1996) and Paul Feyerabend (1962) argued that, although the predecessor and successor theories may use the same terms, such as "mass" and "space" – the meanings of these terms have fundamentally changed. This incommensurability of terms blocks any attempt to connect the two theories via bridge principles; hence, any claim to have reduced one theory to another is unfounded.

The thesis of incommensurability led Feyerabend to endorse a version of theoretical pluralism which he defines as "the simultaneous use of mutually inconsistent theories" to describe a single domain of phenomena (Feyerabend [1965] 1983, p. 149). On this view, scientists ought to invent and develop in detail as many alternatives to the currently accepted theory as possible. Hence, on the taxonomy we introduced above, Feyerabend would best be characterized as a type-II pluralist.

According to the early Feyerabend at least, theoretical pluralism is defended on the methodological grounds that it provides a more rigorous testing of our theories than simply comparing them with "the facts."[10] That is, in so far as these rival alternative theories will be incommensurable with the currently accepted theory, and incommensurable with one another, they will provide a more rigorous testing environment. On this point, however, the views of Feyerabend and Kuhn diverge: Kuhn does not advocate theoretical pluralism as a central methodology of science – except

[10] In so far as Feyerabend's theoretical pluralism is defended on methodological – rather than metaphysical – grounds, it is compatible with the view that there is in principle one correct unified description of the world.

perhaps in periods of so-called crisis. Instead, Kuhn's view remains by and large closer to the eliminative model of reductionism as straightforward theory replacement, or what I have elsewhere referred to as a "serial theoretical monogamy."[11]

One of the clearest contemporary articulations of theoretical pluralism is found in the work of Nancy Cartwright (1995; 1999). In her book *The Dappled World* she writes, "[T]he theory is successful in its domain … Theories are successful where they are successful, and that is that. If we insist on turning this into a metaphysical doctrine, I suppose it will look like metaphysical pluralism" (Cartwright 1999, p. 31). Cartwright defends this pluralism on metaphysical, rather than simply epistemological, grounds. More specifically, she defines her metaphysical version of this thesis as the claim that "nature is governed in different domains by different systems of laws not necessarily related to each other in any systematic or uniform way" (Cartwright 1999, p. 31). This view undermines the reductionist program at its very foundation by denying that there is any theory or set of laws that is universally valid. Thus Cartwright's view seems best described as a version of type-I theoretical pluralism, in so far as she seems to suggest that once a domain of phenomena is delimited, then there is one correct theoretical description of that domain. In other words, her challenge is specifically to the *universality* of physical theories or models, not to their correctness within some circumscribed domain.

Others, such as John Dupré (1995; 1996a; 1996b), have defended a similar thesis under the rubric of "the disunity of science." Dupré, like Cartwright, seeks to defend pluralism on metaphysical grounds: "[T]he picture of science as radically fractured and disunified has a role for metaphysics, and moreover that … set of metaphysical views is entirely plausible" (Dupré 1996b, p. 101). As a philosopher of biology, Dupré's argument for pluralism rests not on an analysis of laws, but rather on a rejection of the following two assumptions that he sees at the foundation of reductionism: first the assumption that there is a unique taxonomy of kinds, and, second, the assumption of causal completeness.[12] According to Dupré, the problem is not that the taxonomies that science provides fail to capture real kinds out there in the world; he thinks they do. Rather, the problem is that these taxonomies are not unique. Dupré argues that one and the same entity can legitimately belong to several different natural kinds, a view he describes as "promiscuous realism."

[11] This phrase was introduced in Bokulich (2006, p. 105). Unlike Kemmeny and Oppenheim's eliminativism, however, Kuhn denies that the observations remain unchanged in the move from one paradigm to another (Kuhn [1962] 1996, pp. 134–5). Although the incommensurability thesis did not lead Kuhn to embrace theoretical pluralism, I shall argue in some detail in the next chapter, that an early formulation of the incommensurability thesis did play a central role in leading the physicist Werner Heisenberg to embrace a version of type-I theoretical pluralism in his account of the relation between classical and quantum mechanics.

[12] Dupré defines causal completeness as "the assumption that for every event there is a complete causal story to account for its occurrence" (Dupré 1996a, p. 99). Regrettably, I will be unable to take the time to discuss this argument here.