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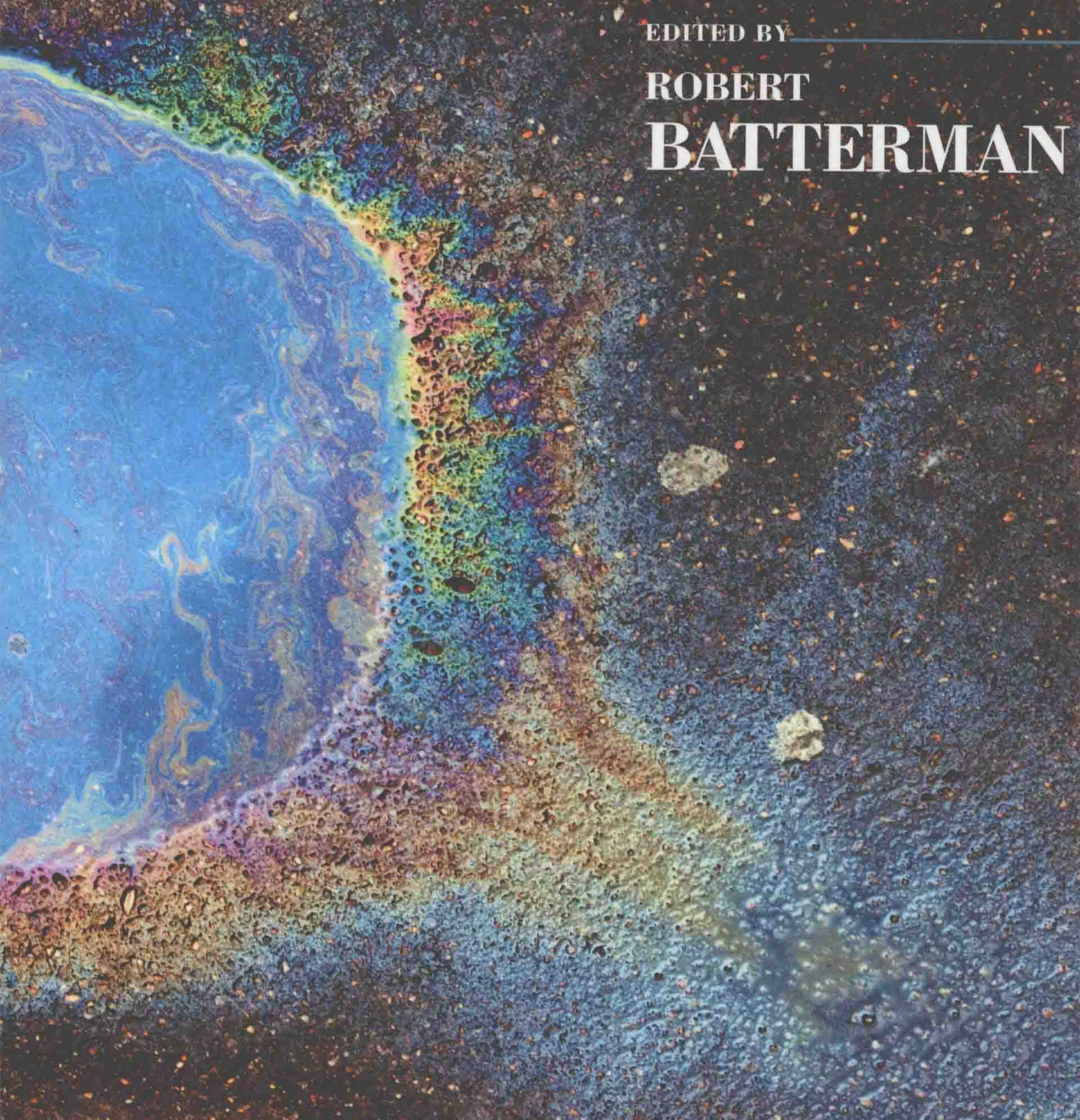
ROBERT BATTERMAN



The Oxford Handbook *of* PHILOSOPHY OF PHYSICS

THE OXFORD HANDBOOK OF

PHILOSOPHY OF PHYSICS

Edited by ROBERT BATTERMAN

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PHILOSOPHY OF PHYSICS

Contributors

Guido Bacciagaluppi is Reader in Philosophy at the University of Aberdeen. His field of research is the philosophy of physics, in particular the philosophy of quantum theory. He also works on the history of quantum theory and has published a book on the 1927 Solvay conference (together with A. Valentini). He also has interests in the foundations of probability and in issues of time symmetry and asymmetry.

Jonathan Bain is Associate Professor of Philosophy of Science at the Polytechnic Institute of New York University. His research interests include philosophy of spacetime, scientific realism, and philosophy of quantum field theory.

Sorin Bangu is Associate Professor of Philosophy at the University of Bergen, Norway. He received his Ph.D. from the University of Toronto and has previously been a postdoctoral fellow at the University of Western Ontario and a fixed-term lecturer at the University of Cambridge, Department of History and Philosophy of Science. His main interests are in philosophy of science (especially philosophy of physics, mathematics, and probability) and later Wittgenstein. He has published extensively in these areas and has recently completed a book manuscript on the metaphysical and epistemological issues arising from the applicability of mathematics to science.

Robert Batterman is Professor of Philosophy at the University of Pittsburgh. He is a Fellow of the Royal Society of Canada. He is the author of *The devil in the details: Asymptotic reasoning in explanation, reduction, and emergence* (Oxford, 2002). His work in philosophy of physics focuses primarily upon the area of condensed matter broadly construed. His research interests include the foundations of statistical physics, dynamical systems and chaos, asymptotic reasoning, mathematical idealizations, the philosophy of applied mathematics, explanation, reduction, and emergence.

Gordon Belot is Professor of Philosophy at the University of Michigan. He has published a number of articles on philosophy of physics and related areas—and one small book, *Geometric possibility* (Oxford, 2011).

Craig Callender is Professor of Philosophy at the University of California, San Diego. He has written widely in philosophy of science, metaphysics, and philosophy of physics. He is the editor of *Physics meets philosophy at the Planck length* (with

Huggett) and the *Oxford handbook of the philosophy of time*. He is currently working on a book monograph on the relationship between physical time and time as we experience it.

Olivier Darrigol is a CNRS research director in the SPHERE/Rehseis research team in Paris. He investigates the history of physics, mostly nineteenth and twentieth century, with a strong interest in related philosophical questions. He is the author of several books including *From c-numbers to q-numbers: The classical analogy in the history of quantum theory* (Berkeley: University of California Press, 1992), *Electrodynamics from Ampère to Einstein* (Oxford: Oxford University Press, 2000), *Worlds of flow: A history of hydrodynamics from the Bernoullis to Prandtl* (Oxford: Oxford University Press, 2005), and *A history of optics from Greek antiquity to the nineteenth century* (Oxford: Oxford University Press, 2012).

Leo P. Kadanoff is a theoretical physicist and applied mathematician who has contributed widely to research in the properties of matter, the development of urban areas, statistical models of physical systems, and the development of chaos in simple mechanical and fluid systems. His best-known contribution was in the development of the concepts of "scale invariance" and "universality" as they are applied to phase transitions. More recently, he has been involved in the understanding of singularities in fluid flow.

John Byron Manchak is an Assistant Professor of Philosophy at the University of Washington. His primary research interests are in philosophy of physics and philosophy of science. His research has focused on foundational issues in general relativity.

Tarun Menon is a graduate student in Philosophy at the University of California, San Diego. His research interests are in the philosophy of physics and metaphysics, particularly time, probability, and the foundations of statistical mechanics. He is also interested in formal epistemology and the cognitive structure of science.

Margaret Morrison is Professor of Philosophy at the University of Toronto. She is the author of several articles on various aspects of philosophy of science including physics and biology. She is also the author *of Unifying scientific theories: Physical concepts and mathematical structures* (Cambridge, 2000) and the editor (with Mary Morgan) of *Models as mediators: Essays on the philosophy of natural and social science* (Cambridge, 1999).

Oliver Pooley is University Lecturer in the Faculty of Philosophy at the University of Oxford and a Fellow and Tutor at Oriel College, Oxford. He works in the philosophy of physics and in metaphysics. Much of his research focuses on the nature of space, time, and spacetime.

Laura Ruetsche is Professor of Philosophy at the University of Michigan. Her *Interpreting quantum theories: The art of the possible* (Oxford, 2011) aims to articulate questions about the foundations of quantum field theories whose answers might hold interest for philosophy more broadly construed.

Simon Saunders is Professor in the Philosophy of Physics and Fellow of Linacre College at the University of Oxford. He has worked in the foundations of quantum field theory, quantum mechanics, symmetries, thermodynamics, and statistical mechanics and in the philosophy of time and spacetime. He was an early proponent of the view of branching in the Everett interpretation as an "effective" process based on decoherence. He is co-editor (with Jonathan Barrett, Adrian Kent, and David Wallace) of *Many worlds? Everett, quantum theory, and reality* (OUP 2010).

Chris Smeenk is Associate Professor of Philosophy at the University of Western Ontario. His research interests are history and philosophy of physics, and seventeenth-century natural philosophy.

Sheldon R. Smith is Professor of Philosophy at UCLA. He has written articles on the philosophy of classical mechanics, the relationship between causation and laws, the philosophy of applied mathematics, and Kant's philosophy of science.

David Wallace studied physics at Oxford University before moving into philosophy of physics. He is now Tutorial Fellow in Philosophy of Science at Balliol College, Oxford, and university lecturer in Philosophy at Oxford University. His research interests include the interpretation of quantum mechanics and the philosophical and conceptual problems of quantum field theory, symmetry, and statistical physics.

Mark Wilson is Professor of Philosophy at the University of Pittsburgh, a Fellow of the Center for Philosophy of Science, and a Fellow at the American Academy of Arts and Sciences. His main research investigates the manner in which physical and mathematical concerns become entangled with issues characteristic of metaphysics and philosophy of language. He is the author of *Wandering significance: An essay on conceptual behavior* (Oxford, 2006). He is currently writing a book on explanatory structure. He is also interested in the historical dimensions of this interchange; in this vein, he has written on Descartes, Frege, Duhem, and Wittgenstein. He also supervises the North American Traditions Series for Rounder Records.

Contents

INTRODUCTION

ROBERT BATTERMAN

When I was in graduate school in the 1980s, philosophy of physics was focused primarily on two dominant reasonably self-contained theories: Orthodox nonrelativisitic quantum mechanics and relativistic spacetime theories. Of course, there were a few papers published on certain questions in other fields of physics such as statistical mechanics and its relation to thermodynamics. These latter, however, primarily targeted the extent to which the reductive relations between the two theories could be considered a straightforward implementation of the orthodox strategy outlined by Ernest Nagel.

Philosophical questions about the measurement problem, the question of the possibility of hidden variables, and the nature of quantum locality dominated the philosophy of physics literature on the quantum side. Questions about relationalism vs. substantivalism, the causal and temporal structure of the world, as well as issues about underdetermination of theories dominated the literature on the spacetime side. Some worries about determinism vs. indeterminism crossed the divide between these theories and played a significant role in shaping the development of the field. (Here I am thinking of Earman's *A Primer on Determinism* (1986) as a particular driving force.)

These issues still receive considerable attention from philosophers of physics. But many philosophers have shifted their attention to other questions related to quantum mechanics and to spacetime theories. In particular, there has been considerable work on understanding quantum field theory, particularly from the point of view of algebraic or axiomatic formulations. New attention has also been given to philosophical issues surrounding quantum information theory and quantum computing. And there has, naturally, been considerable interest in understanding the relations between quantum theory and relativity theory. Questions about the possibility of unifying these two fundamental theories arise. Relatedly, there has been a focus on understanding gauge invariance and symmetries.

However, I believe philosophy of physics has evolved even further, and this belief prompts the publication of this volume. Recently, many philosophers have focused their attentions on theories that, for the most part, were largely ignored in the past. As noted above, the relationship between thermodynamics and statistical mechanics—once thought to be a paradigm instance of unproblematic theory reduction—is now a hotly debated topic. Philosophers and physicists have long implicitly or explicitly adopted a reductionist methodological bent. Yet, over the years this methodological slant has been questioned dramatically. Attention has been focused on the explanatory and descriptive roles of "non-fundamental," *phenomenological* theories. In large part because of this shift of focus, "old" theories such as classical mechanics, once deemed to be of little philosophical interest, have increasingly become the focus of deep methodological investigations.

Furthermore, some philosophers have become more interested in less "fundamental" contemporary physics. For instance, there are deep questions that arise in condensed matter theory. These questions have interesting and important implications for the nature of models, idealizations, and explanation in physics. For example, model systems, such as the Ising model, play important computational and conceptual roles in understanding how there can be phase transitions with specific characteristics. And, the use of the thermodynamic limit is an idealization that (some have argued) plays an essential, ineliminable role in understanding and explaining the observed universality of critical phenomena. These specific issues are discussed in several of the chapters in this volume.

In the United States during the 1970s and 1980s, there was a great debate between particle physicists who pushed for funding of high-energy particle accelerators and solid-state or condensed-matter theorists for whom the siphoning off of so much government funding to "fundamental" physics was unacceptable. A famous paper championing the latter position is Philip Anderson's "More Is Different" (1972). Not only was this a debate over funding, but it raised issues about exactly what should count as "fundamental" physics. While historians of physics have focused considerable attention on this public debate, philosophers of physics have really only recently begun to engage with the conceptual implications of the possibility that condensed matter theory is in some sense just as fundamental as high-energy particle physics.

This collection aims to do two things. First, it tries to provide an overview of many of the topics that currently engage philosophers of physics. And second, it focuses attention on some theories that by orthodox 1980s standards would not have been considered fundamental. It strives to survey some of these new issues and the problems that have become a focus of attention in recent years. Additionally, it aims to provide up-to-date discussions of the deep problems that dominated the field in the past.

In the first chapter, "For a Philosophy of Hydrodynamics," Olivier Darrigol focuses attention on lessons that can be learned from the historical development of fluid mechanics. He notes that hydrodynamics has probably received the least attention of any physical theory from philosophers of physics. Hydrodynamics is not a "fundamental" theory along the lines of quantum mechanics and relativity theory, and its basic formulation has not evolved much for two centuries. These facts, together with a lack of detailed historical studies of hydrodynamics, have kept the theory off the radar.[1] Darrigol provides an account of the development of hydrodynamics as a complex theory—one that is not fully captured by the basic Navier-Stokes equations. For the theory to be applicable, particularly for it to play an explanatory role, a host of techniques—idealizations, modeling strategies, and empirically determined data must come into play. This discussion shows clearly how intricate, sophisticated, and modern the theory of hydrodynamics actually is. Darrigol draws a number of lessons about the structures of phenomenological theories from his detailed discussion, focusing particularly on what he calls the "modular structure" of hydrodynamics.

Continuing the discussion of "old"—but by no means dead or eliminated—theories, Mark Wilson takes on the formidable task of trying to say exactly what is the nature of classical mechanics. A common initial reaction to this topic is to dismiss it: "Surely we all know what classical mechanics is! Just look at any textbook." But as Wilson shows in "What Is 'Classical Mechanics' Anyway?", this dismissive attitude is misleading on a number of important levels. Classical mechanics is like a five-legged stool on a very uneven floor. It shifts dramatically from one foundational perspective to another depending upon the problem at hand, which in turn is often a function of the scale length at which the phenomenon is investigated. In the context of planetary motions, billiards, and simplified ideal gases in boxes, the point-particle interpretation of classical mechanics will most likely provide an appropriate theoretical setting. However, as soon as one tries to provide a more realistic description of what goes on inside actual billiard ball collisions, one must consider the fact that the balls will deform and build up internal stresses upon collision. In such situations, the point-particle foundation will fail and one will need to shift to an alternative foundation, provided by classical continuum mechanics. Yet a third potential foundation for classical mechanics can be found within so-called analytic mechanics, in which the notion of a rigid body becomes central. Here constraint forces (such as the connections that allow a ball to roll, rather than skid, down an inclined plane) play a crucial role. Forces of this type are not wholly consistent with the suppositions central to either the point-particle or continuum points of view. A major lesson from Wilson's discussion is that classical mechanics should best be thought of as constituted by various foundational methodologies that do not fit

[1] Darrigol's recent *Worlds of Flow* fills this lacuna providing an exceptional discussion of the history (Darrigol 2005).

particularly well with one another. This goes against current orthodoxy that a theory must be seen as a formally axiomatizable consistent structure. On the contrary, to properly employ classical mechanics for descriptive and explanatory purposes, one pushes a foundational methodology appropriate at one scale of investigation to its limiting utility, after which one shifts to a different set of classical modeling tools in order to capture the physics active at a lower size scale. Wilson argues that a good deal of philosophical confusion has arisen from failing to recognize the complicated scale-dependent structures of classical physics.

Sheldon Smith's contribution adds to our understanding of a particular aspect of classical physics. In "Causation in Classical Mechanics," he addresses skeptical arguments initiated by Bertrand Russell to the effect that causation is not a fundamental feature of the world. In the context of classical physics, one way of making this claim more precise is to argue that there is no reason to privilege retarded over advanced Green's functions for a system. Green's functions, crudely, describe the effect of an instantaneous, localized disturbance that acts upon the system. It seems that the laws of motion for electromagnetism or for the behavior of a harmonic oscillator do not distinguish between retarded (presumably "causal") and advanced (presumably "acausal") solutions. If there is to be room for a principle of causality in classical physics, then it looks like we need to find extra-nomological reasons to privilege the retarded solutions. Smith surveys a wide range of attempts to answer the causal skeptic in the contexts of the use of Green's functions and the imposition of (Sommerfeld) radiation conditions, among other attempts. The upshot is that it is remarkably difficult to find justification within physical theory for the maxim that causes precede their effects.

The next chapter, by Leo Kadanoff, focuses on condensed matter physics. In particular, Kadanoff discusses progress in physically understanding the fact that matter can abruptly change its qualitative state as it undergoes a phase transition. An everyday example occurs with the boiling water in a teakettle. As the temperature increases, the water changes from its liquid phase to its vapor phase in the form of steam. Mathematically, such transitions are described by an important concept called an order parameter. In a first-order phase transition, such as the liquid vapor transition, the order parameter changes discontinuously. Certain phase transitions, however, are continuous in the sense that the discontinuity in the behavior of the order parameter approaches zero at some specific critical value of the relevant parameters such as temperature and pressure. For a long time there were theoretical attempts to understand the physics involved in such continuous transitions that failed to adequately represent the actual behavior of the order parameter as it approached its critical value. The development of the *renormalization group* in the 1970s remedied this situation. Kadanoff played a pivotal role in the conceptual development of renormalization group theory. In this chapter, he focuses on these developments (particularly, the improvement upon early mean field theories) and on a deeply interesting feature he calls the "extended singularity theorem." This is the idea that sharp, qualitatively distinct, changes in phase involve the presence of a mathematical singularity. This singularity typically emerges in the limit in which the system size becomes infinite. The understanding of the behavior of systems at and near phase transitions requires radically different conceptual apparatuses. It involves a synthesis between standard statistical mechanical uses of probabilities and concepts from dynamical systems theory—particularly, the topological conceptions of basins of attraction and fixed points of a dynamical transformation.

The discussion of the renormalization group and phase transitions continues as Tarun Menon and Craig Callender examine several philosophical questions raised by phase transitions. Their chapter, "Turn and Face the Strange ...Ch-ch-changes," focuses on the question of whether phase transitions are to be understood as genuinely emergent phenomena. The term "emergent" is much abused and confused in both the philosophical and physics literatures and so Menon and Callender provide a kind of road map to several concepts that have been invoked in the increasing number of papers on emergence and phase transitions. In particular, they discuss conceptions of reduction and corresponding notions of emergence: conceptual novelty, explanatory irreducibility, and ontological irreducibility. Their goal is to establish that for any reasonable senses of reducibility and emergence, phase transitions are not emergent phenomena, and they do not present problems for those of a reductionist explanatory bent. In a sense, their discussion can be seen as challenging the importance of the extended singularity theorem mentioned above. Menon and Callender also consider some recent work in physics that attempts to provide well-defined notions of phase transition for finite systems. Their contribution serves to highlight the controversial and evolving nature of our philosophical understanding of phase transitions, emergence, and reductionism.

Jonathan Bain's contribution on "Effective Field Theories" looks at several physical and methodological consequences of the fact that some theories at low-energy scales are effectively independent of, or decoupled from, theories describing systems at higher energies. Sometimes we know what the high-energy theory looks like and can follow a recipe for constructing low-energy effective theories by systematically eliminating high-energy interactions that are essentially "unobservable" at the lower energies. But, at other times, we simply do not know the correct high-energy theory, yet nonetheless, we still can have effective low-energy theories. Broadly construed, hydrodynamics is an example of the latter type of effective theory, if we consider it as a nineteenth century theory constructed before we knew about the atomic constitution of matter. Bain's focus is on effective theories in quantum field theory and condensed matter physics. His discussion concentrates on the intertheoretic relations between low-energy effective theories and their high-energy counterparts. Given the effective independence of the former from the latter, should one think of this relation as autonomous or emergent? Bain contends that an answer to this question is quite subtle and depends upon the type of renormalization scheme employed in constructing the effective theory.

My own contribution to the volume concerns a general problem in physical theorizing. This is the problem of relating theories or models of systems that appear at widely separated scales. Of course, the renormalization group theory (discussed by Kadanoff, Menon and Callender, and Bain in this volume) is one instance of bridging across scales. But more generally, we may try to address the relations between finite statistical theories at atomic and nanoscales and continuum theories that apply at scales 10+ orders of magnitude higher. One can ask, for example, why the Navier-Cauchy equations for isotropic elastic solids work so well to describe the bending behavior of steel beams at the macroscale. At the microscale the lattice structure of iron and carbon atoms looks nothing like the homogeneous macroscale theory. Nevertheless, the latter theory is remarkably robust and safe. The chapter discusses strategies for upscaling from theories or models at small scales to those at higher scales. It examines the philosophical consequences of having to consider, in one's modeling practice, structures that appear at scales intermediate between the micro and the macro.

There has been considerable debate about the nature of symmetries in physical theories. Recent focus on gauge symmetries has led philosophers to a deeper understanding of the role of local invariances in electromagnetism, particle physics, and the hunt for the Higgs' particle. Sorin Bangu provides a broad and comprehensive survey of concepts of symmetry and invariance in his contribution to this volume. One of the most seductive features of symmetry considerations comes out of Wigner's suggestion that one might be able to understand, explain, or ground laws of nature by appeal to a kind of superprinciple expressing symmetries and invariances that constrain laws to have the forms that they do. On this conception symmetries are, perhaps, ontologically and epistemically prior to laws of nature. This raises deep questions for further research on the relationship between formal mathematical structures and our physical understanding of the world.

Gordon Belot also considers issues of symmetry and invariance. His contribution explores the connections between being a symmetry of a theory—a map that leaves invariant certain structures that encode the laws of the theory—and what it is for solutions to a theory to be *physically* equivalent. It is fairly commonplace for philosophers to adopt the idea that, in effect, these two notions coincide. And if they do, then we have tight connection between a purely formal conception of the symmetries of a theory and a methodological/interpretive conception of what it is for two solutions to represent the same physical state of affairs. Belot notes that in the context of spacetime theories there seem to be well-established arguments supporting this tight connection between symmetries and physical equivalence. However, he explores the difficulties in attempting to generalize this connection in contexts that include classical dynamical theories. Belot examines different ways one might make precise the notion of the symmetries of a classical theory and shows that they do not comport well with reasonable conceptions of physical equivalence. The challenge to the reader is then to find appropriate, nontrivial notions of symmetries for classical theories that will respect reasonable notions of physical equivalence.

Yet another type of symmetry, permutation symmetry, is the subject of the chapter by Simon Saunders, entitled "Indistinguishability." He focuses on the proper understanding of particle indistinguishability in classical statistical mechanics and in quantum theory. In the classical case, Gibbs had already (prior to quantum mechanics) recognized a need to treat particles, at least sometimes, as indistinguishable. This is related to the infamous *Gibbs paradox* that Saunders discusses in detail. The concept of "indistinguishability" had meanwhile entered physics in a completely new way, involving a new kind of statistics. This came with the derivation of Planck's spectral distribution, in which Planck's quantum of action h first entered physics. Common wisdom has long held that particle indistinguishability is strictly a quantum concept, inapplicable to the classical realm; and that classical statistical mechanics is anyway only the classical limit of a quantum theory. This fits with the standard view of the explanation of quantum statistics (Bose-Einstein or Fermi-Dirac statistics): departures from classical (Maxwell-Boltzmann) statistics are explained by particle indistinguishability. With this Saunders takes issue. He shows how it is possible to treat the statistical mechanical statistics for classical particles as invariant under permutation symmetry in exactly the same way that it is treated in the quantum case. He argues that the conception of permutation symmetry deserves a place alongside all the other symmetries and invariances of physical theories. Specifically, he argues that the concept of indistinguishable, permutation invariant, *classical* particles is coherent and reasonable contrary to many claims found in the literature.

Margaret Morrison's topic is "Unification in Physics." She argues that there are a number of distinct senses of unification in physics, each of which has different implications for how we view unified theories and phenomena. On the one hand, there is a type of unification that is achieved via reductionist programs. Here a paradigm example is the unification provided by Maxwellian electrodynamics. Maxwell's emphasis on mechanical models in his early work involved the introduction of the displacement current, which was necessary for a field theoretic representation of the phenomena. These models also enabled him to identify the luminiferous aether with the medium of transmission of electromagnetic phenomena. Two aethers were essentially reduced to one. When these models were abandoned in his later derivation of the field equations, the displacement current provided the unifying parameter or theoretical quantity that allowed for the identification of electromagnetic and optical phenomena within the framework of a single field theoretic account. This type of unification was analogous to Newton's unification of the motions of the planets and terrestrial trajectories under the same (gravitational) theoretical framework. However, not all cases of unification are of this type. Morrison discusses the example of the electroweak theory in some detail, arguing that this unificatory success represents a kind of synthetic, rather than reductive, unity. The electroweak theory also involves a unifying parameter, namely, the "Weinberg angle." However, the unity achieved through gauge symmetry is a synthesis of structure, rather than of substance, as exemplified by the reductive cases. Finally, in calling attention to the difficulties with the Standard Model more generally, Morrison notes that yet a different kind of unification is achieved in the framework of effective field theory. This provides another vantage point from which to understand the importance of the renormalization group. Morrison argues for a third type of unification in terms of the universality classes, one that focuses on unification of phenomena but should be understood independently of the type of micro-reduction characteristic of unified field theory approaches.

As noted earlier, there continues to be significant research on foundational problems in quantum mechanics. Guido Bacciagaluppi's chapter provides an up-to-date discussion of work on two distinct problems in the foundations of quantum mechanics that are typically conflated in the literature. These are the problem of the classical regime and the measurement problem. Both problems arise from deep issues involving entanglement and the failure of an ignorance interpretation of reduced quantum states. Bacciagaluppi provides a contemporary and thorough introduction to these issues. The problem of the classical regime is that of providing a quantum mechanical explanation or account of the success of classical physics at the macroscale. It is, in essence, a problem of intertheoretic relations. Contemporary work has concentrated on the role of environmental decoherence in the emergence of classical kinetics and dynamics. Bacciagaluppi argues that the success of appeals to decoherence to solve this problem will depend upon one's interpretation of quantum mechanics. He surveys an ontologically minimalist instrumental interpretation and a standard, ontologically more robust or realistic interpretation.

The measurement problem is the distinct problem of deriving the collapse postulate and the Born rule from the first principles (Schrödinger evolution) of the quantum theory. In examining the measurement problem, Bacciagaluppi provides a detailed presentation of a modern, realistic theory of measurement that goes beyond the usual idealized discussions of spin measurements using Stern-Gerlach magnets. This discussion generalizes the usual collapse postulate and the Born rule to take into account the fact that real measurements are unsharp. It does so by employing the apparatus of positive operator value (POV) measures and observables. The upshot is that the measurement problem remains a real worry for someone who wants to maintain a standard, reasonably orthodox interpretation of quantum theory. Perhaps Everett theories, GRW-like spontaneous collapse theories, and so on are required for a solution.

The Everett, or Many Worlds, interpretation of quantum mechanics is the subject of David Wallace's chapter. It is well known that the linearity of quantum mechanics leads, via the principle of superposition, to the possibility that macroscopic objects such as cats can be found in bizarre states—superpositions of being alive and being dead. Wallace argues that a proper understanding of what quantum mechanics actually says will enable us to understand such bizarre situations in a way that does not involve changing the physics (e.g., as in Bohmian hidden variable mechanics or GRW spontaneous collapse theories). Neither, he claims, does it involve changing one's philosophy by, for example, providing an operationalist interpretation that imposes some special status to the observer or to what counts as measurement, along the lines of Bohr. Such interpretations are at odds with our understanding of, say, the role of the observer in the rest of science. Wallace argues for a straightforward, fully realist interpretation of the bare mathematical formalism of quantum mechanics and claims that this interpretation will make sense of superposed cats, and so on, without changing the theory and without changing our overall