OPEN SYSTEMS
PHYSICS, METAPHYSICS, AND METHODOLOGY

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Contributors

Emily Adlam is an Assistant Professor in the Department of Philosophy at Chapman University.

Luis C. Barbado is a Postdoctoral Researcher at the Institute for Quantum Optics and Quantum Information Vienna and the Faculty of Physics at the University of Vienna.

Časlav Brukner is a University Professor in the Faculty of Physics at the University of Vienna and Scientific Director of the Institute for Quantum Optics and Quantum Information Vienna.

Eddy Keming Chen is an Associate Professor at the University of California, San Diego, and a Fellow of the John Bell Institute for the Foundations of Physics.

Michael E. Cuffaro is an Alexander von Humboldt Fellow and External Member of the Munich Center for Mathematical Philosophy, Ludwig-Maximilians-Universität München.

Gemma De les Coves is a Catalan Institution for Research and Advanced Studies (ICREA) Research Professor of the Universitat Pompeu Fabra in Barcelona.

George Ellis is a Fellow of the Royal Society and Emeritus Distinguished Professor in the Department of Mathematics and Applied Mathematics at the University of Cape Town.

Doreen Fraser is a Professor in the Department of Philosophy at the University of Waterloo.

Henrique Gomes is a Junior Research Fellow in Philosophy of Physics at Oriel College, Oxford University.

Sean Gryb is an Assistant Professor at the University College Groningen of the University of Groningen.

William L. Harper is an Emeritus Professor in the Department of Philosophy at the University of Western Ontario.

Stephan Hartmann is an Alexander von Humboldt Professor and Co-Director of the Munich Center for Mathematical Philosophy, Ludwig-Maximilians-Universität München.

Molly Kao is an Associate Professor in the Department of Philosophy at the University of Montreal.

Adam Koberinski is a Postdoctoral Fellow of the Rotman Institute of Philosophy at the University of Western Ontario.

James Ladyman is a Professor in the Department of Philosophy at the University of Bristol.

Simon Langenscheidt is a Ph.D. Student at the Arnold Sommerfeld Center for Theoretical Physics, Ludwig-Maximilians-Universität München.

Olimpia Lombardi is a Superior Researcher at the University of Buenos Aires and for the Argentine National Scientific and Technical Research Council.

Jørn Kløvfjell Mjelva is a Doctoral Research Fellow in the Department of Philosophy, Classics, History of Art and Ideas at the University of Oslo.

Wayne C. Myrvold is a Professor in the Department of Philosophy at the University of Western Ontario.

Daniele Oriti is a Distinguished Researcher in the Department of Theoretical Physics at Complutense University of Madrid.

Josh Quirke (Ph.D., Birmingham) is an Independent Researcher.

David Sloan is a Reader in Physics at Lancaster University and Chief Scientific Officer of the Foundational Questions Institute.

Karim P. Y. Thébault is an Associate Professor in the Department of Philosophy at the University of Bristol.

Lev Vaidman is an Emeritus Professor in the School of Physics and Astronomy at Tel Aviv University.

David Wallace is the A. W. Mellon Professor in the Department of Philosophy and the Department of History and Philosophy of Science at the University of Pittsburgh.

Alastair Wilson is a Professor in the School of Philosophy, Religion and History of Science at the University of Leeds, and an Adjunct Senior Research Fellow at Monash University.

Acknowledgements

Thanks to Peter Momtchiloff, Henry Clarke, and Imogene Haslam at Oxford University Press for their support and encouragement at various stages of the publication process. We also want to thank the members of our research group on the philosophy of open systems: James Ladyman, Sébastien Rivat, David Sloan, and Karim Thébault; as well as Florian Boge, John Dougherty, Simon Friederich, Gábor Hofer-Szabó, Nick Huggett, Gregg Jaeger, Alyssa Ney, John Norton, Eric Schliesser, Chris Smeenk, Paul Teller, Roderich Tumulka, Harald Wiltsche, and an anonymous external reader for Oxford University Press for their guidance and advice. Finally, MEC thanks his late friend (and dog), T-Rex, for all the long walks that provided opportunities for thinking about the physics of open systems.

This project would not have been possible without the generous financial support of the German Research Council (DFG), through grant number 468374455, and the Alexander von Humboldt Foundation, through an Experienced Researcher Grant to MEC.

Introduction

Michael E. Cuffaro and Stephan Hartmann

The study of open systems is a cornerstone of many scientific disciplines outside of physics. Across the biological, social, and cognitive sciences, systems are commonly understood in terms of their interactions with an environment. This is because, at a fundamental level, the entities studied in these disciplines are rarely, if ever, isolated. Organisms exchange energy and matter with their surroundings, social groups depend on external influences, and cognitive processes are shaped by environmental stimuli. Theories that emphasise openness, such as general systems theory (von Bertalanffy 1988), cybernetics (Wiener 1950), synergetics (Haken 1983), and complex systems theory (Ladyman and Wiesner 2020, Thurner et al. 2018), have been instrumental in shaping modern scientific methodologies. These frameworks allow researchers to analyse and predict the behaviour of dynamically interacting components within larger wholes.

While openness is often taken as a given in the special sciences, physics has historically developed with a strong emphasis on closed-system modelling. The success of Newtonian mechanics, classical thermodynamics, and quantum mechanics has to a large extent relied on the ability to isolate and describe systems in terms of well-defined boundary conditions. Even when physical systems are manifestly open, traditional approaches attempt to account for environmental influences by incorporating them into an effectively closed formalism. This methodological preference raises questions with deep philosophical implications: Does this approach adequately capture the complexities of real-world systems, or does it impose artificial constraints on our understanding of nature? To what extent can open-system phenomena be reduced to closed-system descriptions, and what are the limits of this reduction?

Recent developments suggest that the importance of open systems is gaining increasing recognition within physics. Non-equilibrium thermodynamics, pioneered by Prigogine and Nicolis (1977), has challenged the traditional emphasis on closed equilibrium states, highlighting the role of irreversible processes and emergent structures. Similarly, research in quantum biology (Al-Khalili and McFadden 2015) has underscored the interplay between quantum effects and environmental interactions in biological systems. At the intersection of physics and cognitive science, dynamic causal modelling (Weinberger 2020) provides tools for understanding how information flows through complex networks, while interventionist accounts of causation (Pearl 2009, Woodward 2003) emphasise the role of external influences in shaping system behaviour. These research programs suggest that open-system approaches are not merely useful but, in some cases, essential for advancing our understanding of the physical world. In quantum foundations, research into "quantum causality" has provided new perspectives on the role of environmental interactions in quantum processes. While traditional interpretations of quantum mechanics often rely on a closed-system perspective, recent work in this area challenges this assumption, arguing that a more accurate understanding of the causal structure of quantum phenomena requires that we explicitly consider the openness of the systems involved (Allen et al. 2017, Costa and Shrapnel 2016), shedding new light on the nature of quantum nonlocality and the limits of classical causal explanations (Adlam 2023, Evans 2018, Shrapnel 2019). These developments resonate with broader trends in physics, where the study of complex, adaptive, and information-rich systems increasingly calls for a departure from purely closed-system frameworks.

Despite these advances, the methodological and conceptual challenges posed by open systems remain. How should we formalise openness in physical theories? Are existing mathematical frameworks sufficient, or do we need new theoretical tools? What implications does the shift towards open-system thinking have for the philosophy of science and metaphysics?

In the following chapters, we and our fellow contributors will explore these questions and others in depth. To begin, however, the next section will provide a short discussion of how open systems are understood and analysed in physics. Along the way, we will introduce key concepts that will be essential as the reader progresses through the book. At the end of this introduction, we will summarise the chapters to come, offering a road map for the journey ahead.

1. Modelling Open Systems in Physics

Physical systems can be closed or open in various senses. A *thermodynamically open* system, for instance, is one that exchanges heat or work with its external environment. Some systems of this kind—consider an internal combustion engine propelling a car down the highway, for example—inevitably also exchange material particles with their environment. But not all thermodynamically open systems are also *chemically open* in that sense. Any liquid within a container whose walls are thick enough to exclude chemical interactions between the liquid and a bath within which it has been immersed, but still permit the exchange of heat between the liquid and the bath, is *chemically closed* despite being thermodynamically open. No system aside from, perhaps, the entire universe is *absolutely closed*—i.e., exchanging nothing at all with its environment—at a minimum, every material system in the universe is subject to the influence of the gravitational field. But in practice, even when a system is not strictly closed we often do successfully model it as such when the influence of the environment on the system can be considered to be negligible, or if there are other principled reasons that allow us to ignore it.

Isaac Newton's Corollary VI to his laws of motion (Newton 1999 [1687]: p. 423), for instance, states that a system of bodies moving in any way whatsoever with respect to one another will continue to do so in the presence of equal accelerative forces acting on that system along parallel lines. This makes it possible (see Figure 0.1) to treat the system of Jupiter and its moons, for example, as a (quasi-)closed system even though it is being acted

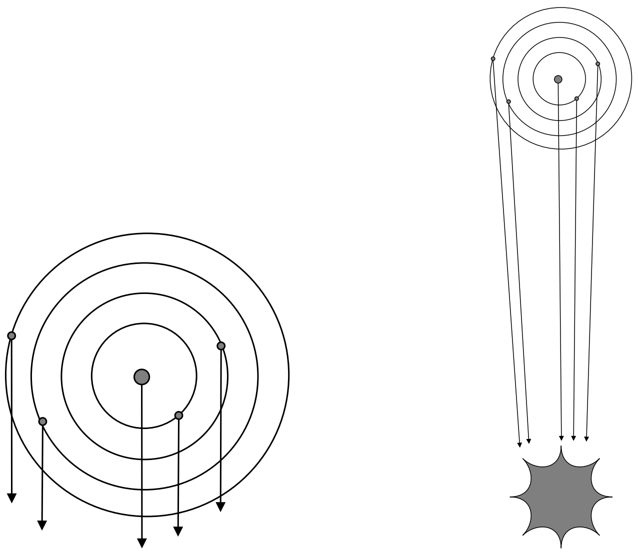

Figure 0.1: The action of the sun on the Jovian system. Although the action of the sun on the Jovian system (the system of Jupiter and its moons) is not exactly equal and parallel (right), because the sun is so far away and so large in comparison to it, its action on the Jovian system is approximately equal and parallel (left), which means that we can appeal to Corollary VI to effectively ignore the action of the sun when reasoning about the Jovian system's internal motions.

upon by the sun. Because of the sun's vast distance from the Jovian system and its relative size, the forces it exerts on that system are essentially equal and parallel and can therefore, by Corollary VI, be neglected, at least up to a certain scale. For further discussion, see DiSalle (2006), Harper (2011), Harper (this volume), and Saunders (2013).

Unsurprisingly, there are systems—such as lasers, spontaneous emission processes, and (quantum-)information processing systems—for which a proper account requires explicitly considering the environment's influence on the system. In many cases, such a system can be modelled by conceptualising it as enclosed within a large 'box', that is itself isolated. That is, we can often accurately represent an (open) system, $\mathcal{S}$, as a subsystem of a larger, isolated composite system, $\mathcal{S} + \mathcal{E}$. This approach is crucial in thermodynamics and statistical mechanics (see Myrvold 2021, chs. 6–8, and Ladyman and Thébault, this volume), as well as in quantum mechanics, which we will now discuss in more detail.

In quantum mechanics, the standard framework (see our own chapter in this volume) relies on wave functions that evolve according to the Schrödinger equation, assuming complete isolation from external influences. However, in reality, most physical systems interact with their environment, leading to more complex behaviour. To address this, physicists use the density matrix formalism, which extends the description of quantum systems to include statistical mixtures of quantum states.

A fundamental distinction in this framework is between pure and mixed states. A *pure state* represents a system with maximal knowledge about its quantum state, meaning it is described by a single wave function. A *mixed state*, by contrast, represents a statistical ensemble of different possible states, reflecting either uncertainty or quantum entanglement (Ismael 2021) arising from the system's interaction with another system. This leads to an important conceptual divide between proper and improper mixtures. *Proper mixtures* arise from classical ignorance—much like flipping a coin and not knowing whether it landed heads or tails. *Improper mixtures*, by contrast, result from abstracting away part of an entangled quantum system (a process known as 'tracing out'). This means that even if a system appears to be in a mixed state, its mixedness may stem from entanglement rather than classical uncertainty.

This distinction is significant for foundational debates in quantum mechanics. If a density matrix describes an improper mixture, should we interpret it as a real physical state of affairs or merely as a tool to describe our partial knowledge? This question relates to the broader discussion of whether quantum states represent reality (i.e., if they are ontic) or knowledge (i.e., if they are epistemic). Furthermore, the density matrix formalism plays a central role in discussions of quantum decoherence (Bacciagaluppi 2025)—the process by which interference effects disappear in macroscopic systems—offering insights into the transition from quantum to classical behaviour.

A key feature of standard quantum mechanics is that the evolution of a system is *unitary*, meaning that information is never lost and probabilities always sum to one. However, when a quantum system interacts with its environment, its evolution is no longer strictly unitary. This leads to dissipation (loss of energy) and decoherence (loss of quantum coherence), which must be accounted for using a more general mathematical framework. The *Lindblad master equation* provides a framework for describing the non-unitary evolution in open quantum systems and ensures that the probabilities here also add up to one.

The Lindblad equation emerges when we consider a specific small quantum system—such as a two-level atom—and model its interaction with a much larger environment, such as an electromagnetic field or a thermal bath. By 'tracing out' the environmental degrees of freedom, we obtain an effective equation for the system itself, capturing both its unitary evolution (governed by the system's Hamiltonian) and the non-unitary effects of dissipation and decoherence. This derivation relies on certain approximations, such as the Born-Markov assumption, which simplifies the interaction by neglecting memory effects in the environment.

Beyond its practical importance, the Lindblad equation raises fundamental philosophical questions about the nature of quantum theory. If all real-world quantum systems interact with their environment, does this mean that unitary evolution is merely an idealisation? Decoherence, as described by the Lindblad equation, is often invoked to explain why macroscopic systems appear classical—why we do not see Schrödinger's cat in a superposition of alive and dead. But does decoherence truly solve the measurement problem, or does it merely postpone it? Some argue that while decoherence explains why certain quantum states become indistinguishable from classical ones, it does not fully account for why measurements yield definite outcomes. This debate highlights why open quantum systems are not only crucial for practical applications such as quantum computing but also central to a deeper understanding of our most fundamental scientific models, theories, and frameworks.

Understanding the role of open systems in physics requires a careful analysis of how we construct and apply scientific models. In general, a *model* is the key representational tool used in science, and it is used to describe a specific system for a particular epistemic or practical purpose—whether for prediction, explanation, or intervention (Frigg and Hartmann 2020). A *theoretical model*, in turn, is usually formulated in the context of a specific *scientific theory*. When multiple theories share a core set of modeling principles, they form what we call a *theoretical framework*. As we have argued elsewhere (Cuffaro and Hartmann 2024), theoretical frameworks can differ in their underlying *view* of how systems should be conceptualised. For example, the *closed systems view* takes isolated systems as the fundamental objects of study, treating interactions with the environment in terms of couplings between otherwise separable systems that, together, can be regarded as closed. The *open systems view*, by contrast, shifts the focus to the ways in which real systems are inherently embedded in their environments, challenging the assumption that closed-system descriptions are always the most fundamental.

This volume brings together seventeen chapters that examine the physical, metaphysical, and methodological questions surrounding open systems, drawing from a range of disciplines. The contributions explore topics ranging from quantum theory to cosmology, with an interdisciplinary reach that extends into biology. Organised into three thematic sections, the book investigates: (i) the open systems view in physics, (ii) historical and contemporary perspectives on open and closed system concepts, and (iii) the broader, including metaphysical, implications for our understanding of the physical world. By weaving together these different perspectives, this collection demonstrates how shifting the focus to open systems offers fresh insights across fields, reshaping not only our understanding of physical systems but also informing wider debates about the nature of reality.

2. Chapter Summaries

Part I: The Open Systems View

The first part of the book begins with *Quantum Theory is About Open Systems*, wherein we introduce the theoretical framework for quantum physics that is usually taken for granted in philosophical and foundational discussions of the topic: Standard Quantum Theory (**ST**), and we consider approaches to interpreting the formalism that take **ST** to be complete in some sense (roughly: “(neo-)Bohrian” and “(neo-)Everettian” approaches). In our chapter, we argue, from the point of view of each, that although **ST** is formulated in accordance with the closed systems view it is, in fact, ontologically committed to open systems in a way that other theoretical frameworks, which also happen to be formulated in accordance with the closed systems view, are not. We take this to suggest that philosophical and foundational progress in quantum theory may be made by, as we have argued in more detail elsewhere, abandoning what we take to be the artificially restrictive closed systems view in favour of the open systems view.

In Chapter 2, Emily Adlam argues that there is a temporal analogue of the open systems view, which she calls *The Temporally Open Systems View* (TOSV), that suggests that our universe should not be thought of as being divisible into autonomous time slices that are describable independently of one another. Rather, according to TOSV, the happenings at a given time generically depend upon the happenings at other times. Adlam argues that, in fact, quantum histories are not decomposable into autonomous temporal slices in the way required by a temporally closed systems view, and she considers the consequences of TOSV for the ontology of quantum theory and for the question of whether the state of the universe should be thought of as pure or mixed.

The book continues with Chapter 3, by Olimpia Lombardi, entitled *The Relative Na-*

ture of Open Quantum Systems. As Lombardi points out, a quantum system can neither be labelled nor assigned a precise trajectory through spacetime. Moreover, quantum systems generically become correlated with one another in ways that challenge the idea that a composite quantum system is composed of independent subsystems. As Lombardi explains, this relative nature manifests itself under a number of different forms: the relativity of entanglement, the identification of systems in the context of the process of decoherence, and the many ways in which a composite quantum system can be decomposed into subsystems. She argues that any view, such as our own open systems view, which takes open systems to be fundamental, is required to take subsystem-relativity into account. Indeed, according to Lombardi, neither the open systems view nor the closed systems view should be considered to be fundamental. Rather, they should be thought of as complementary approaches to quantum physics that need not be considered to be rivals.

Chapter 4, *Quantum Systems Other Than the Universe*, is by David Wallace. In it, Wallace expounds and develops the claim that physics should be understood as the study of autonomous, not necessarily isolated, dynamical systems, rather than as the project to provide an exact description of the whole universe. In the context of quantum theory this means that, in general, we should take quantum systems to be in mixed states with non-unitary dynamics. In Wallace's framework, however, pure states and unitary dynamics nevertheless continue to have a special role, insofar as the non-unitary dynamics of a system is always taken to be explainable by focusing on a restriction of the dynamics of a larger unitary system to the system of interest, where the larger unitary system comprises both the system of interest and its environment. For Wallace, this follows from what he calls "four dogmas of quantum reductionism," which he argues for on methodological and metaphysical grounds: (i) "non-unitarity implies interaction," (ii) "interaction is derived from dilation," (iii) "the dilations that explain interaction are to larger unitary systems," and (iv) those dilations are in accordance with a particular class of well-confirmed quantum theories. He then compares this position with our own open systems view.

Frameworks and metaphysical assumptions are the focus for Doreen Fraser and Adam Koberinski, who end this part of the book with Chapter 5, *Frameworks in Physics: Abstractness, Generality, And the Role of Metaphysics.* By contrast with Cuffaro and Hartmann (2024), who associate theoretical frameworks with sets of motivating metaphysical assumptions (such as those associated with the closed systems view in the case of **ST**); for Fraser and Koberinski, frameworks are, rather, best characterised by their degree of abstractness and their generality of scope. They illustrate the point via detailed analyses of the quantum field-theoretic and statistical-mechanical frameworks, which, they argue, indicate that metaphysical assumptions are not really integral to the content of a framework, though they may enter at the level of particular theories and models. This makes theoretical frameworks, according to Fraser and Koberinski, poor targets for metaphysical analysis or for relative fundamentality claims.

Part II: Concepts of Open and Closed Systems in and Beyond Physics

In the second part of the book, the focus shifts to analyses of some of the specific ways in which the concepts of open and closed systems are and have been used throughout the history of physics, in contemporary physical theories, and beyond. It begins with Chapter 6, *Newtonian Research and the Open Systems View*, by William L. Harper. Harper contrasts Newton's treatment of the sun's action on Jupiter's moons, with his treatment of its action on our own moon, and argues that this illustrates the importance of what he calls the "opening-up" of a model; i.e., the incorporation of parameters in one's model of a system through which that model can subsequently be further developed. Harper argues that although Newton's centre of mass solution for solar system motions treats our solar system as an isolated system, the extraordinarily successful research program to develop corrections taking perturbations due to gravitational interactions into account was very much an open systems methodology.

In Chapter 7, *Blackbody Radiation: The Open and Closed Systems Views and Complementary Reasoning Strategies*, by Molly Kao, Kao recounts the history of the development of Max Planck's blackbody radiation theory, and argues that Planck's treatment of a blackbody system illustrates how both the open and the closed systems view are present in his methodology as two purportedly inconsistent ways of conceptualising the relation between the blackbody and the radiation field. Kao argues that the incorporation of the open systems view, in particular, led to a fundamental, and theoretically fruitful, change in the conception of a physical system. She then considers two different responses to Planck, by James Jeans and Albert Einstein, respectively, and argues that these responses illustrate complementary reasoning strategies that can be thought of as the narrowing and widening of the domain of applicability of a hypothesis, respectively.

Edge modes and boundary charges in gravitational physics, relational dynamics in classical and quantum gravity, and quantum reference frames are the topic of Chapter 8, by Henrique Gomes, Simon Langenscheidt and Daniele Oriti, entitled *Boundaries, Frames and the Issue of Physical Covariance.* In their chapter, the authors argue that these research programmes are, in fact, closely linked, all sharing the general aim to achieve a more realistic modelling of gravitational phenomena. Gomes, Langenscheidt, and Oriti explain how removing standardly employed idealisations from gravitational physics makes a model necessarily perspectival, in the sense that it is then always relative to a particular choice of physical reference frame. They close their chapter with a discussion of a number of broader conceptual implications concerning the influence of observers in physics and speculate regarding the physical limits of objectivity.

According to Luis C. Barbado and Časlav Brukner, one way of interpreting the Bell and Kochen-Specker no-go theorems on interpretations of quantum mechanics is as implying that the notions of "system" and "experimental context" are fundamentally inseparable, which would further imply that a statement like "the spin is up in the x-direction" is an inherently relational statement that relates the configuration of a macroscopic device with what one takes to be a property of the system in that context. In this way, the object that textbook quantum mechanics treats as a formally closed system is regarded as not actually physically isolated, since it corresponds to the physical relation the system holds with a macroscopic environment. From the perspective of quantum mechanics, however, referencing a macroscopic device assumes the existence of infinite resources, which, as noted by Barbado and Brukner, leads to conceptual difficulties when applied to situations where such resources are not available. In search of an alternative way of cashing out this approach to the no-go theorems, in Chapter 9, *Relational Objectivity in the Presence of Finite Quantum Resources*, Barbado and Brukner consider the concept of a spin network, originally introduced by Roger Penrose, as a potential way of formalising quantum theory that goes beyond standard quantum mechanics and in particular allows for a description, in the presence of finite resources, that is inherently relational and inseparable between system and experimental context.

The last two chapters of Part II deal with more general questions. According to James Ladyman and Karim P. Y. Thébault, making the distinction between an open and a closed system requires that we, first of all, precisely specify some characteristic quantity that will be conserved if and only if the system is closed. Open systems are then those for which conservation of that quantity fails. This is the core of the conceptual framework, for the disambiguation of scientific language regarding open and closed systems, designed and defended by Ladyman and Thébault in Chapter 10, *Open Systems and Autonomy.* Ladyman and Thébault show how open systems, in this framework, can have well-posed dynamical equations that display various senses of autonomy, and need not always be embeddable within a larger system. They argue that the argument that the universe must be subject to unitary time evolution conflates different senses of closed, and that it is an open question whether we should model our universe as an open or a closed quantum system.

The second part of the book ends with Chapter 11, by George Ellis, entitled *Biological Emergence: a Key Exemplar of the Open Systems View.* According to Ellis, all biological entities are open systems, with various kinds of influences impacting upon them from their surrounding environment, which in turn elicit various kinds of responses. In his chapter, Ellis explains that the existence of modular hierarchical structures is what enables the functional complexity that is required for biological emergence (i.e., the emergence of novel and robust behaviour at a given level of description) to arise. Ellis then explains that due to an organism's openness to its environment, the precise state of all of its constituent particles is insufficient to determine the future; but that organisms have developed, through Darwinian evolution, processes to cope with this: on short timescales, on developmental and evolutionary timescales, and at the societal level. As for the largest context of all, Ellis asks: "should the universe itself be regarded as an open system?" Ellis appeals to quantum theory and to cosmology to argue that the answer is yes.

Part III: The Physics and Metaphysics of Worlds and Universes

Cosmology, the universe, and the worlds that, on one interpretation of quantum mechanics, make it up are the subject of the final part of the book, which begins with Chapter 12, *Open Systems as Metaphysically Fundamental: Some Questions*, by Jørn Kløvfell Mjelva, Josh Quirke, and Alastair Wilson, who consider the question of what to make of the concept of the physical universe, on the supposition that open systems, rather than closed systems, are taken to be metaphysically fundamental. After critically unpacking the idea, expressed in Cuffaro and Hartmann (2024), that the physical universe might be best conceived of as an open system, Mjelva, Quirke, and Wilson then explore and unpack the physical and metaphysical consequences of an alternative precisification of the open systems view, namely the idea that there may simply be no such thing as the cosmos, and that physical reality is indefinitely extensible in the sense that every physical system, without exception, should be thought of as a subsystem of some larger system.

Chapter 13, by Sean Gryb and David Sloan, is entitled *How Closed is Cosmology?* Gryb and Sloan begin with the question: "What is a closed system?" After critically surveying the standard responses, they propose a solution that leads to a number of remarkable conclusions, such as that the universe is describable as behaving like an open system with a natural arrow of time. They argue that a number of seemingly unusual features of their proposal only seem surprising because of the inadequacy of naive definitions of what it means to be closed. Gryb and Sloan argue that the appropriate notion of closure in cosmology is dynamical closure, and they discuss some further interesting features of models that are closed in this sense; for instance, that in a growing class of models the autonomous system obtained can be integrated through the big bang.

According to Eddy Keming Chen, although being a realist about quantum theory means being a realist about the universal quantum state, realism leaves undecided the question of whether the quantum state of the universe must be pure and represented by a wave function, or whether it can be mixed and represented by a density matrix. The position called *Density Matrix Realism* is an elaboration and defence of the latter position. In Chapter 14, Chen clarifies the thesis by comparing it with its rival, Wave Function Realism, contrasts it with more general versions of the thesis (including our own open systems view), and addresses a number of what he calls "frequently asked questions" concerning density matrix realism as it relates to issues such as the intelligibility of the thesis, physical equivalence, and theoretical virtues like Occam's Razor.

In Chapter 15, *Conservation Laws in the Many-Worlds Interpretation*, Lev Vaidman argues that on the Many-Worlds Interpretation of quantum theory, although our universe is represented by a unitarily evolving highly entangled wave function, we only perceive a tiny part of the global wavefunction, and the quantum state of this (i.e., our) 'world' is an effectively open system that evolves non-unitarily. Vaidman then analyses the consequences, of questioning the statement that within a world conservation laws hold only for ensembles of measurements, on this conception of a world as an open system, and he proposes a possible resolution of the black hole evaporation paradox.

Do closed (quantum) systems actually exist? In Chapter 16, *Quantum Theory: Ideals, Infinities and Pluralities*, Gemma De les Coves argues that, (i) because no system is ever completely isolated from its environment, (ii) because closure assumes the existence of a radical object-subject split, and (iii) because the description of a closed system necessarily involves an infinity that cannot be instantiated in the world, the answer is no. With regard to (iii), the case of quantum theory is particularly interesting. Quantum theory stands out among other physical theories insofar as describing an ideal closed quantum system does not require an infinity in the dimension of the system. Nevertheless, as De les Coves argues, a number of further infinities are required in the description of such a system even in quantum theory. But if no closed quantum systems exist, how should we then conceive of the universe as a whole? De les Coves puts forth the following thesis: rather than conceiving of the universe as ideal, or singular, it should be conceived of as a plurality.

In the final chapter of the book, Chapter 17, entitled *Perspective Duality as a Physical Requirement*, Wayne C. Myrvold points out that the actual practice of science is unlike the idealised picture that is typically presupposed in much of the philosophy of physics literature, wherein the focus of analysis is on fictitious systems conceived of as wholly isolated from their environments. Myrvold explains how, in practice, one models only a small fraction of a given system's degrees of freedom, and that these constitute, in effect, an open system. Far from being a mere expedient, Myrvold argues that there is a valuable lesson to be learned from this, which is encapsulated in the stance toward physical theory that he calls "perspective duality”: that although (i) a fundamental physical theory should be capable of being formulated without mentioning terms such as ‘system’, ‘apparatus’, and ‘environment’, (ii) any physical theory worth considering as a fundamental theory should also be capable of not embracing everything at once whenever it is used to describe a given system.

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