INTRODUCTION

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1 THE PHILOSOPHY OF PHYSICS TODAY

In the last forty years, philosophy of physics has become a large and vigorous branch of philosophy, and so has amply won its place in a series of Handbooks in the philosophy of science. The reasons for its vigour are not far to seek. As we see matters, there are two main reasons; the first relates to the formative years of analytic philosophy of science, and the second to the last forty years.

First, physics had an enormous influence on the early phase of the analytic movement in philosophy. This influence does not just reflect the fact that for the logical positivists and logical empiricists, and for others such as Russell, physics represented a paradigm of empirical knowledge. There are also much more specific influences. Each of the three main pillars of modern physics — thermal physics, quantum theory and relativity — contributed specific ideas and arguments to philosophical debate. Among the more obvious influences are the following.

Thermal physics and the scientific controversy about the existence of atoms bore upon the philosophical debate between realism and instrumentalism; and the rise of statistical mechanics fuelled the philosophy of probability. As to quantum theory, its most pervasive influence in philosophy has undoubtedly been to make philosophers accept that a fundamental physical theory could be indeterministic. But this influence is questionable since, as every philosopher of science knows (or should know!), indeterminism only enters at the most controversial point of quantum theory: viz., the alleged "collapse of the wave packet". In any case, the obscurity of the interpretation of quantum theory threw not only philosophers, but also the giants of physics, such as Einstein and Bohr, into vigorous debate: and not only about determinism, but also about other philosophical fundamentals, such as the nature of objectivity. Finally, relativity theory, both special and general, revolutionized the philosophy of space and time, in particular by threatening neo-Kantian doctrines about the nature of geometry.

These influences meant that when the analytic movement became dominant in anglophone philosophy, the interpretation of modern physics was established as a prominent theme in its sub-discipline, philosophy of science. Accordingly, as philosophy has grown, so has the philosophy of physics.

But from the 1960s onwards, philosophy of physics has also grown for a reason external to philosophy. Namely, within physics itself there has been considerable

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interest in foundational issues, with results that have many suggestive repercussions for philosophy. Again, there have been various developments within physics, and thereby various influences on philosophy. The result, we believe, is that nowadays foundational issues in the fundamental physical theories provide the most interesting and important problems in the philosophy of physics. We have chosen the topics for this volume in accord with this conviction. In the next Subsection, we will articulate some of these foundational issues, and thereby introduce the Chapters of the volume.

2 CURRENT FOUNDATIONAL ISSUES IN PHYSICS

We will first discuss these issues under five headings. The first three correspond to the three pillars of modern physics mentioned in Section 2.1; i.e. thermal physics, quantum theory and relativity theory. The fourth and fifth concern combinations of these pillars; and lead to speculations about the future of physics. These five headings will provide a way of introducing most of this volume's Chapters, albeit not in the order in which they occur. Then, after these five headings, we will introduce the volume's remaining two Chapters.

2.1 Thermal physics

Controversies about the foundations of thermal physics, especially the characterization of the approach to equilibrium, have continued unabated since the days of the field's founding fathers, such as Maxwell and Boltzmann. Some aspects of the original controversies can be seen again in modern discussions. But the controversies have also been transformed by the development of several scientific fields; especially the following three, which have grown enormously since the 1960s:

(i) classical mechanics, and its offspring such as ergodic theory and chaos theory;

(ii) quantum thermal physics; and

(iii) cosmology, which nowadays provides a very detailed and so fruitful context for developing and evaluating Boltzmann's bold idea that the ultimate origin of the "arrow of time" is cosmological.

In this volume, the foundations of thermal physics is represented by the Chapters by Uffink and by Emch, who cover classical and quantum aspects, respectively. Among the topics Uffink discusses, two receive special attention: the evolution of Boltzmann's views, and the mathematical framework of stochastic dynamics. Emch adopts the formalism of algebraic quantum statistical mechanics, and reviews many results about that formalism's notion of equilibrium, i.e. KMS states. Two other Chapters also provide a little stage-setting for Uffink and Emch, though without pursuing the relation to thermal physics: viz. the Chapters by Butterfield on classical mechanics, and by Ellis on cosmology.

2.2 Quantum theory

Since the 1960s, the physics community has witnessed a revival of the debates about the interpretation of quantum theory that raged among the theory's founding fathers. In the general physics community, the single most influential author has no doubt been John Bell, not only through his non-locality theorem and the many experiments it engendered, but also through his critique of the "Copenhagen orthodoxy" and his sympathy towards the pilot-wave and dynamical collapse heterodoxies. But in more specialist communities, there have been other crucial factors that have animated the debate. Mathematical physicists have developed a deep understanding of the various relations between quantum and classical theories. Since the 1970s, there has been progress in understanding decoherence, so that nowadays, almost all would accept that it plays a crucial role in the emergence of the classical world from quantum theory. And since the 1990s, the burgeoning fields of quantum information and computation have grown out of the interpretative debates, especially the analysis of quantum non-locality.

In this volume, these topics are taken up by Dickson, Landsman and Bub. Dickson surveys the formalism of non-relativistic quantum theory, and some of the main interpretative issues, including empirical content, quantum uncertainty, the measurement problem, and non-locality. For the most part, Landsman reviews from the perspective of mathematical physics the relations between quantum and classical theories. In particular, he discusses various approaches to quantization and the rigorous treatments of the classical limits $\hbar \to 0$ and $N \to \infty$. But Landsman also includes discussions of the Copenhagen interpretation and decoherence. Finally, Bub presents some central ideas and results about quantum information and quantum computation. As a backdrop to this, he also briefly reviews classical information and computation; and he ends by proposing some provocative morals about the interpretation of quantum theory.

2.3 Relativity theory

The decades since the 1960s have seen spectacular developments, for both theory and experiment, in general relativity and cosmology. But this Renaissance has also been very fruitful as regards foundational and philosophical issues. Mathematical relativists have continued to deepen our understanding of the foundations of general relativity: foundations which, as mentioned in Section 1, were recognized already in the 1920s as crucial for the philosophy of space and time. And the recent transformation of cosmology from a largely speculative enterprise into a genuine science has both brought various philosophical questions closer to scientific resolution, and made other philosophical questions, e.g. about method and explanation in cosmology, much more pressing.

In this volume, these topics are represented by the Chapters by Malament, Belot and Ellis. Malament first expounds classical relativity. Then he discusses three special topics: the definition of simultaneity in special relativity, the geometrization of Newtonian gravity, and the extent to which causal structure determines spacetime geometry. Belot's main aim is to give a clear statement of the "problem of time" as it occurs in classical general relativity; and to do that, he first reviews the way time is represented in simpler classical theories, including mechanics. (Belot's Chapter thereby complements Butterfield's: both expound aspects of classical Hamiltonian theories, and stress how some of these aspects reappear in quantum theories.) Ellis first reviews the present state of relativistic cosmological theory and its observational basis; and then investigates nine philosophical themes, including the anthropic principle and the possible existence of multiverses.

So much by way of introducing some foundational issues, and this volume's corresponding Chapters, arising *within* one of the three pillars: thermal physics, quantum theory and relativity. We turn to issues arising from combining the pillars — or rather, parts of them! We have already adumbrated the combination of the first and second: viz., in quantum thermal physics, reviewed here by Emch. It is the combination of the second and third — quantum theory and relativity — which we must now address. We shall do so under two headings, corresponding to the distinction between special and general relativity. The first corresponds, of course, to quantum field theory, which forms such a deep and well-established framework for particle physics. The second corresponds to the quantum theory of gravity — which unfortunately still remains only a hope and a goal.[1]

2.4 Quantum field theory

Although there are relativistic quantum mechanical theories of a fixed number of particles, by far the most important framework combining quantum theory and special relativity is quantum field theory. Broadly speaking, the foundational issues raised by quantum field theory differ from quantum theory's traditional interpretative issues, about measurement and non-locality (cf. *Quantum theory,* §2.2 above). There are two points here.

(i) Although quantum field theory of course illustrates the latter issues just as much as elementary quantum theory does, it apparently cannot offer a resolution of them. The measurement problem and the puzzles about non-locality arise so directly from the unitarity and tensor-product features of quantum theories, as to be unaffected by the extra mathematical structures

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[1] Our image of three pillars prompts the question: what about the combination of thermal physics and relativity? When Einstein's special theory of relativity won acceptance, the rush was on to revise the various branches of classical physics to make them properly relativistic. In the case of thermodynamics, this program produced disputes about the Lorentz transformation properties of the thermodynamic quantities of heat, temperature and entropy that persisted well into the 1970s; (see [Liu, 1994] for an overview of this debate). As for classical general relativity theory, there does not currently exist a statistical mechanics that incorporates the "gravitational entropy of the universe", and it seems unlikely that there can be such a theory. But for all anyone knows, the ideas of thermal physics may play a crucial role in the hoped-for quantum theory of gravity. There are hints to that effect from, for example, black hole thermodynamics, the Unruh effect, and Hawking radiation. These topics are discussed briefly in Rovelli's chapter.

and physical ideas supplied by quantum field theory.[2] And accordingly, it has seemed to most workers to be wisest to pursue the traditional interpretative issues within non-relativistic quantum theory: if you identify a problem in a simple context, but are confident that it is not an artefact of the context's simplicity, it is surely wisest to attack it there. (And as shown in this volume by Dickson's and Landsman's Chapters, that context is by no means "really simple": non-relativistic quantum theory, and its relation to classical theories, provides an abundance of intricate structure to investigate.)

(ii) On the other hand, there are several foundational issues that are distinctive of quantum field theory. Perhaps the most obvious ones are: the nature of particles (including the topic of localization), the interpretation of renormalization, the interpretation of gauge structure, and the existence of unitarily equivalent representations of the canonical commutation relations.

In this volume, these topics are taken up by 't Hooft and by Halvorson and Müger. First, 't Hooft provides an authoritative survey of quantum field theory, from the perspective of particle physics. Among the main topics he expounds are: the quantization of scalar and spinor fields, Feynman path integrals, the ideas of gauge fields and the Higgs mechanism, renormalization, asymptotic freedom and confinement.

Halvorson and Müger discuss a smaller and distinctively foundational set of issues, using the apparatus of algebraic quantum field theory. (So their use of the algebraic approach complements the uses made by Emch and Landsman.) They discuss the nature of particles and localization, non-locality, the assignment of values to quantities (i.e. the measurement problem) and the definability of quantum fields at individual spacetime points. But they devote most of their effort to the Doplicher-Haag-Roberts theory of superselection. This theory yields deep insights into crucial structures of quantum field theory: in particular, the set of representations, the relation between the field and observable algebras, and gauge groups.

2.5 Quantum gravity

Finally, we turn to the combination of quantum theory with general relativity: i.e., the search for a quantum theory of gravity. Here there is of course no established theory, nor even a consensus about the best approach for constructing one. Rather there are various research programmes that often differ in their technical aims, as well as their motivations and conceptual frameworks. In this situation, various

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[2] In some respects relativistic QFT makes the measurement problem worse. In non-relativistic quantum mechanics, the collapse of the state vector is supposed to happen instantaneously; so in the relativistic setting, one would have to develop some appropriate analogue. On the other hand, the modal interpretation of ordinary QM — which arguably provides the best hope for a no-collapse account of quantum measurement — faces formidable obstacles in relativistic quantum field theory; (see [Clifton, 2000] and Halvorson and Müger, this volume, Section 5).

foundational issues about the "ingredient" theories are cast in a new light. For example, might quantum gravity revoke orthodox quantum theory's unitarity, and thereby *en passant* solve the measurement problem? And does the general covariance (diffeomorphism invariance) of general relativity represent an important clue about the ultimate quantum nature of space and time?

In this volume, these and related questions are taken up by Rovelli. He also presents details about other topics: for example, the subject's history, the two main current programmes (string theory and loop quantum gravity), and quantum cosmology. Ellis' Chapter also discusses quantum cosmology. In this way, and indeed by addressing other fundamental questions about the idea of an "ultimate" physical theory, Ellis's Chapter provides a natural complement to Rovelli's.

So much by way of introducing Chapters that correspond to our initial three pillars of modern physics, or to combinations of them. We turn to introducing the volume's remaining two Chapters. Here our intention has been to provide Chapters whose discussions bridge the divisions between physical theories, and even those between our three pillars. In this connection, it seemed to us that of the various possible themes for such a cross-cutting discussion, the two most appropriate ones were determinism and symmetry.[3]

Accordingly, Earman discusses how determinism fares in a wide class of theories: his examples range from classical mechanics to proposals for quantum gravity. He also addresses the relations between determinism and other issues: in particular, predictability, the nature of spacetime, and symmetry. Symmetry in classical physics is given a wide-ranging survey by Brading and Castellani. Among other topics, they discuss: Curie's principle, the advent of group theory into physics, canonical transformation theory, general covariance in general relativity, and Noether's theorems. Various aspects of symmetry and invariance in quantum physics are discussed in the Chapters by Dickson, Emch, Halvorson, and Landsman. But a synoptic overview of this complex topic remains to be written — which we hope will be taken as a challenge by some of our readers.

Let us sum up this introduction to the Chapters that follow, with two comments that are intended to give the prospective reader — perhaps daunted by the many pages ahead! — some courage.

First, it is obvious that by our lights, there is no sharp line between philosophy of physics and physics itself. So it is no surprise that some of the best work in philosophy of physics is being done by physicists (as witnessed by several contributions to this volume). No surprise: but certainly, to be welcomed. Conversely, to the traditionally trained philosopher, work by philosophers of physics is liable to look more like physics than philosophy. But for us, this blurring of disciplinary boundaries is no cause for concern. On the contrary, it represents an opportunity for philosophy to enrich itself. And in the other direction, philosophers can hope

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[3] Other good candidates include the "direction of time", or irreversibility, and the constitution of matter. But adding chapters on these or other cross-cutting themes would have made the volume altogether too long.

that the foundations, and even philosophy, of physics can be a source of heuristic ideas for physics. Or at least, physicists' interest in foundational questions now offers philosophers of physics the opportunity of fruitful discussion with physicists.

But agreed: this enrichment of philosophy does not come for free. And the need to master technical material which is often difficult can be a barrier to entering the philosophy of physics. In designing this volume, our response to this problem has of course been, not to try to lower the barrier, at the cost of scholarship and of fostering illusory hopes: rather our strategy has been to commission Chapters that cover their chosen topics as expertly and completely as possible. So to the reader, our message is simple: take heart! Once you are over the barrier, new vistas open for the philosophy of science.

3 OUTLOOK: HALFWAY THROUGH THE WOODS

Finally, we would like to set the stage for this volume, by making two connected comments about the present state of fundamental physics. Though it may seem naive or hubristic for philosophers to make such comments, we believe it is worth the risk. For we think that at the present juncture fundamental physics is unusually open to contributions from philosophical reflection; and it will be clear from our comments that together they represent an invitation to the reader to make such contributions! The first comment concerns the amazing successes of present-day physics; the second, the fact that so much remains to be understood.

3.1 Successes

First, we want to celebrate the extraordinary achievements of modern physics; specifically of quantum theory and relativity theory. We propose to do this by emphasising how contingent, indeed surprising, it is that the basic postulates of relativity and quantum theory have proved to be so successful in domains of application far beyond their originally intended ones.

Examples are legion. We pick out two examples, almost at random. Why should the new chronogeometry introduced by Einstein's special relativity in 1905 for electromagnetism, be extendible to mechanics, thermodynamics and other fields of physics? And why should the quantum theory, devised for systems of atomic dimensions (10^{-8} cm) be good both for scales much smaller (cf. the nuclear radius of ca. 10^{-12} cm) and vastly larger (cf. superconductivity and superfluidity, involving scales up to 10^{-1} cm)? Indeed, much of the history of twentieth century physics is the story of the consolidation of the relativity and quantum revolutions: the story of their basic postulates being successfully applied ever more widely.

The point applies equally well when we look beyond terrestrial physics. We have in mind, first, general relativity. It makes a wonderful story: the theory was created principally by one person, motivated by conceptual, in part genuinely philosophical, considerations — yet it has proved experimentally accurate in all kinds of astronomical situations. They range from weak gravitational fields such as occur in the solar system — here it famously explains the minuscule portion of the precession of the perihelion of Mercury (43" of arc per century) that was unaccounted for by Newtonian theory; to fields 10,000 times stronger in a distant binary pulsar — which in the last twenty years has given us compelling (albeit indirect) evidence for a phenomenon (gravitational radiation) that was predicted by general relativity and long searched for; and to exotic objects such as black holes. But general relativity is not the only case. Quantum theory has also been extraordinarily successful in application to astronomy: the obvious example is the use of nuclear physics to develop a very accurate and detailed theories of nucleosynthesis in the very early universe, and of stellar structure and evolution.

Indeed, there is a more general point here, going beyond the successes of relativity and quantum theory. Namely, we tend to get used to the various unities in nature that science reveals — and thereby to forget how contingent and surprising they are. Of course, this is not just a tendency of our own era. For example, nineteenth century physics confirmed Newton's law of gravitation to apply outside the solar system, and discovered terrestrial elements to exist in the stars (by spectroscopy): discoveries that were briefly surprising, but soon taken for granted, incorporated into the educated person's 'common sense'. Similarly nowadays: the many and varied successes of physics in the last few decades, in modelling very accurately phenomena that are (i) vastly distant in space and time, and-or (ii) very different from our usual laboratory scales (in their characteristic values of such quantities as energy, temperature, or pressure etc.), reveal an amazing unity in nature. General theoretical examples of such unity, examples that span some 200 years, are: the ubiquitous fruitfulness of the field concept; and more specifically, of least action principles. For a modern, specific (and literally spectacular) example, consider the precision and detail of our models of supernovae; as confirmed by the wonderful capacity of modern telescope technology to see and analyse individual supernovae, even in other galaxies.

3.2 Clouds on the horizon

And yet: complacency, let alone triumphalism, is not in order! Current physics is full of unfinished business — that is always true in human enquiry. But more to the point, there are clouds on the horizon that may prove as great a threat to the continued success of twentieth century physics, as were the anomalies confronting classical physics at the end of the nineteenth century.

Of course, people differ about what problems they find worrisome; and among the worrisome ones, about which problems are now ripe for being solved, or at least worth addressing. As philosophers, we are generalists: so we naturally find all the various foundational issues mentioned above worrisome. But being generalists, we will of course duck out of trying to say which are the closest to solution, or which are most likely to repay being addressed! In any case, such judgments are hard to adjudicate, since intellectual temperament, and the happenstance of what one knows about or is interested in, play a large part in forming them.

But we would like to end by returning to one of Section 2's "clouds": a cloud which clearly invites philosophical reflection, and perhaps contributions. Namely, the problem of quantum gravity; in other words, the fact that general relativity and quantum theory are yet to be reconciled. As mentioned in Section 2.5, Rovelli (this volume) discusses how the contrasting conceptual structures of the "ingredient" theories and the ongoing controversies about interpreting them, make for conflicting basic approaches to quantum gravity.

But we want here to emphasise another reason why we still lack a successful theory, despite great effort and ingenuity. In short, it is that the successes of relativity and quantum theory, celebrated in Comment 3.1 above, conspire to deprive us of the relevant experimental data.

Thus there are general reasons to expect data characteristic of quantum gravity to arise only in a regime of energies so high (correspondingly, distances and times so short) as to be completely inaccessible to us. To put the point in terms of length: the value of the Planck length which we expect to be characteristic of quantum gravity is around 10^{-33} cm. This is truly minuscule: the diameters of an atom, nucleus, proton and quark are, respectively, about 10^{-8}, 10^{-12}, 10^{-13}, and 10^{-16} cm. So the Planck length is as many orders of magnitude from the (upper limit for) the diameter of a quark, as that diameter is from our familiar scale of a centimetre!

We can now see how quantum gravity research is in a sense the victim of the successes of relativity and quantum theory. For those successes suggest that we will not see any "new physics" intimating quantum gravity even at the highest energies accessible to us. The obvious example is quasars: these are typically a few light-days in diameter, and yet have a luminosity 1000 times that of our galaxy (itself 100,000 light-years across, containing a hundred billion stars). They are the most energetic, distant (and hence past!) celestial objects that we observe: they are now believed to be fuelled by massive black holes in their cores. Yet suggestions, current thirty years ago, that their stupendous energies and other properties that we *can* observe, could only be explained by fundamentally new physics, have nowadays given way to acceptance that "conventional physics" describing events *outside* the black hole's event-horizon can do so. (Agreed, we expect the physics deep inside the black hole, in the vicinity of its singularity, to exhibit quantum gravity effects: but if ever a region deserved the name "inaccessible", this is surely one!) So the situation is ironic, and even frustrating: quantum gravity research is a victim of its ingredient theories' success.

In any case, the search for quantum gravity is wide open. In closing, we would like to endorse an analogy of Rovelli's [1997]. He suggests that our present search is like that of the mechanical philosophers such as Galileo and Kepler of the early seventeenth century. Just as they struggled with the clues given by Copernicus and Brahe, *en route* to the synthesis given by Newton, so also we are "halfway through the woods". Of course we should be wary of too grossly simplifying and periodizing the scientific revolution, and *a fortiori* of facile analogies between different historical situations. Nevertheless, it is striking what a "mixed bag" the doctrines of figures such as Galileo and Kepler turn out to have been, from the perspective of the later synthesis. For all their genius, they appear to us (endowed with the anachronistic benefits of hindsight), to have been "transitional figures". One cannot help speculating that to some future reader of twentieth century physics, enlightened by some future synthesis of general relativity and quantum theory, our current and recent efforts in quantum gravity will seem strange: worthy and sensible from the authors' perspective (one hopes), but a hodge-podge of insight and error from the reader's!

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