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Mélanie Frappier
Derek H. Brown
Robert DiSalle *Editors*

Analysis and Interpretation in the Exact Sciences

Essays in Honour of William Demopoulos

Springer

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Preface

This volume was inspired by a conference at the University of Western Ontario in May, 2008, in honour of Professor William Demopoulos. It is not a faithful record of the conference; the papers here are not necessarily those presented, and the authors are neither all nor only the conference participants. But the volume reflects the conference in the best ways: as a celebration of Bill's career by his closest philosophical friends and collaborators, and—more importantly—as a contribution to the continuing philosophical project that his career represents.

As much as it has been an occasion to reflect on Bill's work over the past four decades, there is nothing retrospective about this collection: its contents are a cross-section of some of the most important contemporary thinking on some of the most urgent problems in present-day philosophy of science. In spite of the diversity of topics and problems that the papers address, this is not an eclectic collection. The authors have not simply been brought together by their personal ties to Bill. They are also linked by their ties to the view of philosophy that his work represents: a view according to which the conceptual problems of science derive their special interest from their connections to the deepest questions of analytic philosophy.

The editors owe a personal debt to Bill for creating—through his writing and teaching—the philosophical atmosphere in which this collection came to be. Mélanie Frappier and Derek H. Brown were Bill's students, and Robert DiSalle has been his junior colleague for over two decades, and we are all in his debt for an intellectual formation not to be found anywhere else in the philosophical world. Mélanie and Derek wrote their doctoral theses with Bill between 1999 and 2004, on very disparate topics: Mélanie on Heisenberg's notion of interpretation, and Derek on the philosophy of colour perception; they came to appreciate not only the breadth of Bill's philosophical interests, but also the underlying unity of his philosophical methodology. Twenty students wrote their doctoral dissertations under Bill's supervision, on topics including Frege and Carnap, the philosophy of physics and the philosophy of mathematics, logic and the philosophy of science, theory of perception and theory of computation, the philosophy of language and the philosophy of mind. Now academics in various institutions across Canada and around the world, they do not form a school of thought—for Bill has never encouraged disciples—but are schooled in an approach to philosophy that brings the tools of the analytic tradition to a remarkable range of philosophical problems.

The editors thank first and foremost the authors represented here for their contributions and their patience. We are of course deeply grateful to all of the participants in the conference, and to the many students who contributed to its smooth operation. We thank Lucy Fleet, our editor at Springer, for her generous assistance and encouragement, Sona Ghosh for her work on the index, and Adam Schipper, Emily McCrae, and Cameron Roberts for editorial assistance. The only previously published chapter is that of the late Itamar Pitowsky; this paper is an extension of his ‘Betting on the outcomes of measurements: a Bayesian theory of quantum probability’, *Studies in History & Philosophy of Modern Physics 34*(3), (2003) 395–414. We would like to thank Itamar’s widow, Liora Lurie, for permission to publish the extended version, and Emma Williams of Elsevier for her efforts toward securing permission from the publisher. The conference was made possible by a grant from the Social Sciences and Humanities Research Council of Canada. SSHRC also provided support for the editorial work on this volume. Preparation of the volume benefited from financial support from the University of King’s College, and from a Brandon University Research Committee Grant. To all of these institutions we express our thanks.

Introduction

This collection brings together the work of philosophers whose individual interests are very diverse. They nevertheless share a view of conceptual analysis and theoretical interpretation, and their essays concern the points of intersection between analytic philosophy and the philosophy of the sciences. More precisely, the essays collected here concern the connections between theoretical knowledge in mathematics and physics, perception and linguistics, on the one hand, and the conceptual foundations of knowledge in general on the other. The volume's guiding idea is that in contemporary philosophy of science there are profound problems of theoretical interpretation—problems that transcend both the methodological concerns of general philosophy of science, and the technical concerns of philosophers of the particular sciences.

A fruitful approach to these problems combines the study of scientific detail with the kind of conceptual analysis that is characteristic of the modern analytic tradition. Such an approach is shared by some of the most important philosophers of our time: some primarily known as analytic philosophers, some as philosophers of science, but all deeply aware that the problems of analysis and interpretation link these fields together. This volume brings those philosophers together for a rare and historic collaboration.

Analytic philosophy and the philosophy of science, as we now know them, emerged in the late 1800s. Analytic philosophy arose from 19th-century insights into the nature of logic, the connections between logic and language, and the connections of both to the traditional concepts of metaphysics and epistemology; philosophy of science arose from the growing self-consciousness of scientists, especially physicists, concerning their methods, their previously-unexamined assumptions, and the relations between their mathematical and physical foundations. Both fields played essential parts in revolutionary intellectual developments. Analytic philosophy is inseparable from the emergence and elaboration of modern logic and axiomatics, while 19th-century philosophy of science informed the development of relativity theory and quantum mechanics. From these remarkable achievements, each field developed on its own well-defined path.

The sharp separation between the two paths is in some ways an artifact of later 20th-century thinking. At the beginning of the last century they shared many fundamental motivations, methods, and intellectual traditions. For instance, Bertrand Russell, on one side, and Albert Einstein, on the other, saw that progress in their respective endeavors demanded some insight into a common set of problems: the proper definition of fundamental concepts; the nature and function of formal axiomatic structures, and, generally, the relation between our conceptual or linguistic structures and the world of experience. Indeed, a central aim of the logical positivist program—whatever their difficulties in fulfilling it—was to unite the achievements of the new philosophy of physics with the developing analytic picture of logic and language, into a unified account of theoretical knowledge.

The many weaknesses of the logical positivists' work may seem to have cast doubt on the very possibility of such a synthesis of philosophy of science with the analytic tradition. Over the past several decades, the aims of logical positivism have been eclipsed by a philosophy of science focused either on empirical methodology, or on historical and internal questions regarding the practices and foundational problems of particular sciences—a salutary corrective, no doubt, to a philosophical movement that had come to appear rather distant from actual scientific practice. At the same time, however, the original unifying aim of the positivist tradition has not diminished in philosophical importance. On the contrary, it has once again become a central point of philosophical research and discussion. There are two main reasons for this development. First, over the past decade or so, there has been a growing interest in and appreciation of the logical positivist tradition. Along with a better historical understanding of the positivists' efforts—partly obscured in the general philosophical reaction against them—has come a better sense of the philosophical importance of the problems that they tried unsuccessfully to solve. To say this is not to defend the logical positivists against the criticisms that eventually overcame their work in the later 20th century. It is only to acknowledge that, in the course of that critical reaction, some of those problems were prematurely set aside, to the detriment of philosophy of science as an organic part of philosophy in general.

The second, more important reason is that, outside of the dominant currents in earlier post-positivist philosophy of science, work on those earlier foundational problems has never really ceased. But it has taken on a fundamentally different character. Rather than beginning from a foundational conception that purports to be paradigmatic for all scientific knowledge—such as the positivistic idea of fixing empirical meaning by convention—the contemporary analytic tradition starts from local conceptual difficulties in particular fields of knowledge—scientific, mathematical, logical or linguistic—and confronts the problems of meaning and interpretation that emerge from these. Such problems inevitably concern the content and application of concepts in the sciences, and so they require combining conceptual analysis with a detailed understanding of the sciences themselves. If philosophy of science is to acquire a general understanding of the nature of theoretical knowledge, and the relation between its formal and empirical aspects, it will have to emerge from analytical and interpretive work of this kind.

Contents

Part III Foundations of Physics

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Chapter 1
Analysis and Interpretation in the Philosophy of Modern Physics

Robert DiSalle

1.1 Introduction

The interpretation of a physical theory might appear to have an irreducibly subjective dimension: it may seem to require an a priori commitment—on philosophical grounds quite external to the theory in question—to an idea of what sort of metaphysical framework, or ontological picture, would make the theory completely intelligible. This, at least, would not be an obviously unreasonable inference from the history of the philosophy of physics over the last century. Indeed, it seems obviously reasonable from the history of debate over the foundations of quantum mechanics, where the problem of interpretation appears to be very weakly constrained. In interpreting quantum theory, for example, it might appear that any aspect of the classical picture may be preserved, provided one is willing to make appropriate adjustments elsewhere in the theory. Generally, the interpretive problems give rise to competing views of what quantum mechanics "is about": the relation between the measuring-apparatus and the things measured (Heisenberg 1927); or the nature of probability (Pitowsky 2006); or quantum information theory (Bub 2004). In light of these controversies, there would appear to be considerable arbitrariness about precisely what aspects of the classical picture should be preserved, or rejected, by any particular interpretation of quantum mechanics.

It would be worthwhile to consider to what extent these difficulties of interpretation depend on the peculiarities of quantum mechanics—and the phenomena that it represents—and to what extent they reflect the interpretive problems that face any theory of mathematical physics. By the same token, it would be worthwhile to consider whether, from the study of theories whose interpretations appear to be more straightforward, some insight could be gained that would be useful for the study of quantum mechanics. In the case of relativity theory, arguably, the general formalism of space-time geometry appears to offer a straightforward interpretation, at

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least in these two senses: it expresses the essential physical content of the theory, and captures the essential points at which our world departs from the pre-relativistic picture of it. This is not to deny that disputes over the interpretation of space-time theory continue, or that those disputes are philosophically and scientifically significant. I do suggest, however, that the problem of interpreting space-time theory has been comparatively tractable, and has even been illuminating for the philosophical study of mathematical theories and their representations of the physical world. I also suggest that the insight gained from this study has emerged from the treatment of interpretation as, essentially, a task of conceptual analysis. To characterize this approach to analysis, and its bearing on the interpretation of physical theories, is the aim of this paper.

1.2 On Conceptual Analysis in Science

The term "conceptual analysis" has many senses, but the sense that matters here was articulated by Demopoulos: "the practice of recovering a central feature of a concept in use by revealing the assumptions on which our use of the concept depends" (2000, p. 220). This approach to conceptual analysis is thus distinct from, for example, approaches that are primarily linguistic, or rooted in anything like a Kantian understanding of analyticity. For here the target of analysis is neither the typical uses of the relevant term, nor its putative meaning. Rather, the analysis is responsible to a body of scientific knowledge and practice, in which the concept plays an implicit role, not necessarily reflected in the explicit theoretical discourse of the science, but constitutive of its conceptual structure, and indispensable to theoretical reasoning within the structure.

Conceptual analysis in this sense plays an important role in the philosophy of the exact sciences, and particularly in the understanding of conceptual innovation. Demopoulos took this view of Frege's use of "Hume's principle" in his account of the natural numbers (Demopoulos 1998, 2000). Briefly, in Frege's analysis, "Hume's principle" constitutes a definition of numerical identity:

> For any concepts *F* and *G*, the number of *F*s is identical with the number of *G*s if and only if the *F*s and the *G*s are in one-one correspondence. (Demopoulos 2000, p. 210).

On the basis of this principle, the basic laws of arithmetic can be derived. One noteworthy aspect of this principle, historically, was the difficulty of determining its precise philosophical status, and thereby the status of the arguments that Frege built upon it. It would seem to be a questionable basis on which to construct the natural numbers, since it appears to presuppose the notion of number, and therefore to make the construction circular. For this reason, some defenders of Frege (e.g., Wright 1997) have urged that Hume's principle be understood as purely a stipulation, and therefore evaluated only on its contribution to the framework that it defines.[1]

[1] See also Chapter 7, this volume.

Demopoulos, in contrast, recognizes it as a conceptual analysis, one that "captures a central feature of our notion of number and. . .reveals the assumptions on which our conception of their infinity may be based" (2000, p. 220). As a conceptual analysis it therefore carries an epistemic weight beyond that of a mere stipulation; rather than fixing by fiat the employment of the relevant concept, it captures explicitly the implicit basis of an established conceptual scheme. In addition to clarifying this aspect of Frege's argument, Demopoulos' account sheds light on a kind of fundamental principle that has the form and plays the constitutive role, in that science to whose foundation it belongs, of an a priori principle, but is not an "analytic truth" in the sense of being a logical truth, or a conventional definition, and therefore is not trivially true. It is "analytic of" the relation of numerical identity, not by stipulation, but because it is responsible to our pre-analytic notion of numerical identity, the notion that is at work in our mathematical reasoning.

> The plausibility of the idea that Hume's principle is analytic of the concept of numerical identity depends on the plausibility of a conceptual analysis; but the truth of the principle that expresses this analysis depends on the presuppositions of the framework of which the analysis *is* an analysis. (Demopoulos 2000, p. 222).

In this case the relevant presuppositions are obviously mathematical, but Demopoulos's characterization is far more general and, as we will see, equally illuminating of cases where the presuppositions are empirical.

One distinguished such case is Poincaré's (1902) analysis of the foundations of spatial geometry, which brings to light the presuppositions that constitute our most basic notion of space. Pursuing a thought first developed by Helmholtz (1870), Poincaré showed that our simplest conception of the structure of space, as manifested in our capacity for judgments of spatial orientation and position, emerges from the primitive assumption of the free mobility of rigid bodies. This is not typically an explicit belief, of course, but it is implicit in our conception of spatial relations as relations of perspective, and of spatial changes as changes of perspective—changes that we can effect, negate, and combine at will. As operations that can be arbitrarily iterated and combined, as well as inverted, these simple spatial shifts embody the most primitive conception of a group. The intuitive evidence of geometrical constructions, and hence of constructive proofs, has its origins in our intuitive familiarity with these operations; indeed, the question whether any particular geometrical structure applies to space derives its empirical significance from our ability to carry out such operations. Hence the well known conclusion of Helmholtz and Poincaré, that the study of spatial geometry is nothing but the study of the group of displacements.[2] This kind of argument might be mistaken to be a reductive analysis that explains away space by deriving it from a more primitive, non-spatial level of description. But the argument evidently does not derive space from something more primitive than space; rather, it identifies the most primitive spatial principle, a structural feature of the most primitive experiences of motion.

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[2] See Helmholtz (1870) and Poincaré (1902, chapter 4); see also DiSalle (2006, chapter 3).

Such an identification is therefore the result of a conceptual analysis. The temptation to regard it as reductive arises from a naïve metaphysical view, on which space is taken to be given to us as a sort of *thing*, and the fundamental question is taken to be whether it exists on its own, or emerges from some deeper level of reality. But Poincaré's analysis does not take any such view for granted, nor any such question as well posed. Rather, it seeks to characterize what it is to have an experience of space, and what are the presuppositions underlying our ability to form a conception of space, and of our orientation with respect to the other things in it. Like Frege's characterization of numerical identity, it is analytic of an aspect of our conceptual scheme; the important difference from the case of arithmetic is that this elementary mathematical scheme is not absolutely general, but makes essential use of empirical assumptions.

In physics, the most striking case of a conceptual analysis with profound theoretical consequences—the case that became paradigmatic for many physicists and philosophers who came after—was Einstein's analysis of simultaneity (1905). From the point of view of logical positivism, Einstein's argument for special relativity started from an "epistemological" or "operational" analysis of the concept of time, which carries the unfortunate suggestion that Einstein was merely applying an epistemological rule for the definition of theoretical terms by means of measurement procedures. But Einstein's proposals for the practical determination of simultaneity—apart from being, at best, extreme idealizations—are only one of the steps in his analysis. The first step is the initial recognition that, in the conceptual difficulties facing electrodynamics, the deeper problem lay in unacknowledged assumptions about the measurement of space and time, which in turn depended on unacknowledged assumptions about simultaneity. Merely to discern that the concept of simultaneity was crucially implicated in these problems was itself a notable achievement of conceptual analysis. But the central point of Einstein's analysis uncovers the precise connection between the concept of simultaneity and the apparent contradiction between the light-postulate and the relativity principle. The conceptual framework within which the two principles are in conflict, Einstein shows, rests on assumptions about simultaneity whose empirical significance is in doubt; in particular, it rests on the assumption that simultaneity is absolute, in the specific sense that it is invariant for systems in relative motion. On the one hand, one can't begin to construct a frame of reference, and thereby to represent motion, without establishing a criterion of simultaneity. On the other hand, the natural criterion of simultaneity, by means of light-signaling, is challenged by the surprising observation that the speed of light appears to be invariant and isotropic. Lorentz's theory explains that observation, of course, by the hypothesis that length-contraction and time-dilatation compensate for predicted variations in the speed of light. On Einstein's analysis, however, without some alternative way of determining absolute simultaneity, the invariance of measures of length and time becomes questionable as well. Einstein proposes, instead, that the invariance of the speed of light reinforces its place as the natural criterion of simultaneity, and the invariance group of electrodynamics as the natural invariance group of physics. It follows, however, that simultaneity—and therefore time and length—are relative.[3] A conceptual analysis of such subtlety can hardly be portrayed as just an application of the verification theory of meaning, or as the stipulation of an empirical meaning for a concept (simultaneity) that had previously lacked one (cf. Reichenbach 1949, pp. 290–291). In a manner similar to that of Frege's analysis, it characterizes a concept through its role in an established theoretical system, with the difference that the analysis must reconcile the conceptual scheme with new and surprising empirical facts.

The study of conceptual analysis in science has illuminated an aspect of conceptual change that had challenged philosophers of science in the aftermath of Kuhn (1970a): the possibility of objective comparison, or even rational engagement, between theoretical perspectives that are founded on radically different conceptual frameworks. In retrospect, to call this a problem of "incommensurability" was perhaps an overstatement from the beginning. Among physicists, for example, at least since the time of Galileo, there has been sufficient consensus at any given time about the aims of theoretical physics—that is, about the sort of problems to be solved and the requirements for successful solutions, that even scientists of radically opposed conceptual standpoints have found it possible to agree on the relative empirical merits of theories. It has been correspondingly straightforward, from a methodological point of view, to justify revolutionary changes by the improvements they bring about in the general standard of empirical evidence.

Still, one might argue that a central Kuhnian argument had not been answered: the eventual accumulation of evidence for a new framework hardly seems to justify the initial enthusiastic embrace of it, which Kuhn had characterized as more like a "conversion" than a process of scientific evaluation (Kuhn 1970a). To the agents of these historical transformations—theoretical innovators such as Galileo or Einstein—there were compelling rational arguments for conceptual revision. But for Kuhn such arguments were "necessarily circular," reflecting only the philosophical predilections of those making them, and persuasive only to those already converted to their point of view (Kuhn 1970b). The focus on conceptual analysis, in the sense pursued by Demopoulos, places this issue in a new light. It is possible to see the most important conceptual transformations in physics as explicitly motivated by analyses of this sort, analyses that uncover the presuppositions guiding the use and misuse of central theoretical concepts, and expose the challenges to these presuppositions raised by new empirical discoveries. In this process of analysis we find a historical and philosophical dimension to the so-called "paradigm shift" that had completely eluded the Kuhnian school: a rational philosophical engagement where Kuhn had seen only a clash of incommensurable philosophical prejudices. What emerges from such engagement is not merely a novel theoretical perspective, but also a deeper understanding of the old perspective, and the inadequacies in its conceptual foundations that empirical progress has brought to light.

[3] This is a brief outline of an argument that is elaborated at length in DiSalle (2006), Chapter 4, and DiSalle (2010).

Thus the focus on conceptual analysis has led to a better understanding of conceptual change, and, more generally, a better understanding of the interaction between philosophy and science—between philosophical analysis and empirical investigation as sources of scientific knowledge. At the same time, and in a closely connected manner, it provides an illuminating perspective on two problems of interpretation: first, how it is possible to give a philosophical interpretation for a physical theory that is not founded in any particular subjective philosophical viewpoint, but instead is revealing of the conceptual essence of the theory itself; second, and more generally, how to understand scientific theories as structures with interpretations, and thereby how their abstract principles manage to say something about the physical world.

1.3 On Principle Theories and Their Interpretation

Einstein's convincing argument for special relativity, evidently, established the theory as the conceptual framework within which other classical theories, in addition to electrodynamics, would have to be reformulated, insofar as the Lorentz transformations were established as the symmetry group of physics in general, and a requirement for theories of particular interactions. Einstein attempted to draw a general distinction between theories that form such a general framework for physics, and specific theories constructed within the constraints of such a framework. This is his celebrated distinction between "principle theories" and "constructive theories," a typology that has been very much discussed,[4] but whose relevance to our present themes is worth pointing out. Einstein's own words express the distinction most clearly:

> [Constructive theories] attempt to build up a picture of the more complex phenomena out of the materials of a relatively simple formal scheme. Thus the kinetic theory of gases seeks to reduce mechanical, thermal, and diffusion processes to molecular motions. . . . [Principle theories] use not the synthetic but the analytic method. Their starting-point and basis are not hypothetical elements, but empirically based general characteristics of natural processes, principles from which mathematically formulated criteria are developed, which the various processes or the theoretical representations of them have to satisfy. . . .The advantages of constructive theories are completeness, adaptability, and intuitive evidence [*Anschaulichkeit*]. The advantages of principle theories are logical completeness and security of the foundations. (Einstein 2002, p. 206).

Einstein presented the special and general theories of relativity as the examples of principle theories, and it is obvious from the foregoing why special relativity should be the best example, being evidently an empirically-derived theory that sets requirements for all natural processes. Moreover, the contrast between Einstein's theory and Lorentz's becomes still more evident: Lorentz's theory of the electron is a constructive theory, constructing an account of electrons moving in the ether

[4] See Bub (2005) and this volume, below, for a particularly illuminating discussion of Einstein's distinction and its contemporary relevance.

to account for the apparent invariance of the speed of light; Einstein elevates the impossibility of detecting variations in the velocity of light to a general principle of nature, creating a principle theory by adopting as fundamental something that Lorentz had hoped to explain.

This distinction has a direct bearing on the question of interpretation. One reason for regarding special relativity as interpretively straightforward is that the theory itself is, in a crucial sense, an interpretation: it gives an interpretation of simultaneity that results in the relativistic picture of space and time, and it re-interprets the equations of Lorentzian electrodynamics by articulating them within that picture. It is a principle theory precisely because it interprets the phenomenon that puzzled Lorentz as the answer to all the central puzzles of electrodynamics, subsuming the null result of the Michelson-Morley experiment with the phenomenal symmetries of electrodynamics under the fundamental principle of relativity. This is not to say that special relativity is not susceptible of further interpretation. On a somewhat extended construal of interpretation, general relativity may be said to have re-interpreted the special theory as a limiting case. In the more restricted sense that is relevant here, special relativity was given a satisfactory interpretation by Minkowski (1908, 1909) as the theory of space-time in four dimensions, with a pseudo-Euclidean metric; it is Minkowski's interpretation that fully reveals the revisions that the theory forces on existing theory, which constitute a new geometrical picture of space and time. Within that new spatio-temporal setting, the geometrical presuppositions of existing physical theories must be revised. Precisely because they have such consequences for other physical theories, to understand the revisions that they require is a central task for the interpretation of principle theories.

> Interpretations of principle theories aim to explain their relation to the theories they replace. Interpretations are therefore concerned with the nature of the transitions between theories. (Demopoulos, 1974, p. 721)

Minkowski's reconstruction of special relativity is not universally accepted as the model for a satisfying interpretation,[5] but it does give a particularly clear representation of the transition from a Newtonian to a relativistic framework.

This understanding of the interpretation of principle theory reappears, implicitly, in some of Heisenberg's remarks on the interpretation of quantum mechanics.[6] Early in the history of quantum mechanics, at least, Heisenberg suggested a rather minimal account of what is required for an interpretation of a theory:

> We believe we have gained '*anschaulich'* [intuitive or visualizable] understanding of a physical theory if, in all simple cases, we can grasp the experimental consequences qualitatively and see that the theory does not lead to any contradictions. (Heisenberg 1927, p. 172)

We may see this minimal requirement as a defense of the intelligibility of the new quantum mechanics and, by the same token, a definition of a kind of intelligibility

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[5] Bub (2005) articulates the lessons that can be learned for the interpretation of quantum mechanics from Minkowski's interpretation of relativity. For a contrary view, see Brown and Timpson (2006).

[6] For a detailed and illuminating treatment of this subject, here only sketched, see Frappier (2004).

to which, in the experimental situation of the time, quantum mechanics had a better claim than its predecessors. It is not necessary to accept Heisenberg's interpretation to acknowledge that it is, at least, an attempt at an analytic interpretation after the pattern of Einstein's argument for the relativity of simultaneity. His argument for the uncertainty relations represents them as expressing an analogous process of conceptual analysis: new empirical information questions the empirical significance of certain classical concepts, and a new empirical foundation is proposed in which those concepts are radically revised. The experimental barrier to a complete determination of the state of a physical system is reconstructed as a fundamental principle. Heisenberg's comparison of his argument with Einstein's thus has at least an element of truth:

> According to relativity theory, the word "simultaneous" admits of a definition in no other way than through experiments in which the velocity of light propagation enters essentially. If there were a "sharper" definition of simultaneity, for example by signals that propagate infinitely fast, relativity theory would be impossible. . . .The case is similar with the definition of the concepts, "position of the electron," "velocity," in quantum theory. All the experiments that we can perform toward the definition of these words necessarily contain an uncertainty. . . . If there were experiments that made possible a sharper determination of p and q than that corresponding to [the uncertainty relations], quantum mechanics would be impossible. (Heisenberg 1927, p. 179)

The comparison expressly highlights the consequences for classical concepts of a specific pattern of empirical facts, one obviously not contemplated in the construction or the traditional application of those concepts, and fatal to what would have been expected to be a straightforward extension of them to microscopic events.

Indeed, it is precisely this analytical aspect of the argument that is clouded by Heisenberg's discussion of physical disturbances of particles by the measurement apparatus; it is as if, having shown that the interpretation of the measurements requires a revision of classical concepts, he goes on to offer an explanation of the uncertainty relations within the classical framework. If one were to follow carefully the example of Einstein's argument for relativity, one would conclude that the phenomena have failed to provide any grounds for extending those concepts to a causal theory of the measurement interaction, just as, in the former case, the phenomena had provided no basis on which to define a frame-independent measure of simultaneity. Despite the incoherence of the theoretical context in which it is placed, however, Heisenberg's argument, insofar as it bears the comparison with Einstein, illustrates the view of interpretation as a task of analysis: first, as a task of identifying the essential principles of the theory, insofar as they are motivated or required by the phenomena; second, as a task of determining where and how the theory forces revisions in the previous conceptual framework. On the whole, Heisenberg's argument is an attempt to follow Einstein's example of taking what is a puzzle, within an existing framework, as the founding principle of a new principle theory. To treat a theory as a principle theory, in this way, is to set aside a certain familiar type of explanatory project, e.g. to give a causal reconstruction of the observed isotropy of light propagation or of the incompatibility of observables. Instead, we ask what constraints the theory's principles impose on any such theoretical reconstruction, by the criteria that it imposes on all natural processes. It follows naturally that such an interpretation will clarify the theory's relation to its predecessor.

While Einstein's typology is rightly regarded as a philosophically useful one, it is, in retrospect, suggestive rather than perfectly clear.[7] If our purpose is not to represent Einstein's intention faithfully, but to articulate a distinction that sheds light on the problem of interpretation, then we should consider more carefully the notion of "criterion" that is associated with principle theories. Einstein's remark about the comparative advantages of principle and constructive theories somewhat confuses this issue. It suggests that we might be free to adopt, or at least to try to develop, a theory of either sort, depending purely on how well their respective advantages suit our purposes. What this suggestion overlooks is the peculiar connections that can obtain between particular principle and constructive theories—more crucially, the relations that may obtain when a particular principle theory counts among the essential presuppositions of a particular constructive theory. In such a case it would make no sense to speak of a choice between principle and constructive theories, since the former would be a conceptual prerequisite for the construction of the latter; moreover, any conceptual problems of the principle theory, and any resolution of them that led to an important revision of the theory, would have to have serious consequences for the constructive theory, even for the very possibility of such a theory. This representation may not be entirely faithful to Einstein's actual thinking on the subject.[8] But I suggest that this view of the respective roles of principle and constructive theories does capture the situation of special relativity, as a principle theory precisely in Einstein's sense, and also more broadly as a conceptual constraint upon constructive theories that may be developed within its domain.

For a clear view of this situation, we ought to take seriously, and consider in more detail, the notion that principle theories express "criteria" that must be satisfied by natural processes and the theories that represent them. We can understand this in a very narrow sense, as referring to constraints that we take to be binding on all physical processes, expressing impossibilities or limitations on possibilities, in the manner of the laws of thermodynamics. In the case of special relativity, we can point to the impossibility of detecting motion relative to the ether, and the impossibility of accelerating a massive particle to the speed of light. Clearly, to respect that limit is a requirement on a constructive theory within a relativistic world. Yet it's not immediately obvious that such a restriction provides a compelling argument for the transition to relativity. One might contrast Einstein with Lorentz in the following way: Lorentz offered a constructive theory of the apparent invariance of the velocity of light, while Einstein accepted the invariance as fundamental and explicable, and adopted it as one of the principles of his principle-theory. But both positions are

[7] Flores (1999) clarifies many aspects of Einstein's distinction by re-formulating it as the distinction between "framework" and "interaction" theories, a formulation that not only captures key aspects of relativity and quantum mechanics, but also their kinship with Newtonian mechanics as a theory of the same type.

[8] See Brown (2005) and Brown and Timpson (2006). But see Hagar (2008) for a response to Brown.

compatible with the fundamental principle, insofar as Lorentz's theory will certainly not violate it; the essential distinction is that Lorentz does not accept the principle as fundamental. This same attitude is exemplified by Poincaré (1905), who placed much emphasis on the relativity principle, and on the impossibility of detecting motion through the ether, without abandoning the idea of an underlying rest-frame corresponding to the ether. It would appear that Einstein's adoption of the principle-theory of relativity is no more than a proposal to treat as fundamental what Lorentz treats as derived—not without good reasons, the broad outlines of which might be found in his remarks on the respective merits of principle and constructive theories.

If we consider the notion of criterion in a broader philosophical sense, moving from physical to conceptual possibilities, we arrive at a more compelling view of Einstein's conceptual analysis. The philosophical significance of the analysis is that it eliminates, in effect, the choice between a principle and a constructive theory as the solution to the problems of electrodynamics. It exhibits the speed of light as, indeed, the natural criterion of simultaneity, but it also explicates the essential role of this criterion in the construction of a frame of reference. Evidently, however, it cannot be the basis for constructing Newtonian frames of reference: it is an "absolute" criterion in the sense that it is founded in an invariant law of physics, but it results in the relativity of simultaneity, by determining different sets of simultaneous events in different inertial frames. Therefore it provides no basis on which the theoretical concepts presupposed by Lorentz—invariant simultaneity, length, and time—can be empirically constructed. It follows that it provides no conceptual framework on which to build a constructive theory of the Lorentz transformations. That by itself is not a fatal objection to any constructive theory, but only an acknowledgment that Einstein's starting-point allows no room for such a theory. The fatal objection is that the constructive theory has no starting point; the spatio-temporal framework in which its central question is posed has, because of newly-emerging facts of electrodynamics, lost its empirical underpinnings. Of course it is possible in principle that absolute simultaneity, and all that depends on it, could derive an objective criterion from some further empirical discovery. That would reveal that the world has surprising new features, but would not cast doubt on the objectivity of Einstein's conceptual analysis, relative to the facts as then known, or on the uniqueness of the interpretation to which it leads.

This understanding of principle theories clarifies some aspects of a recent controversy, concerning whether special relativity can be, or ought to be, interpreted as a constructive theory.[9] I have little to add to this debate, but it is helpful to see the question from the present perspective on principle theories. The "kinematical part" of Einstein's 1905 argument establishes the fundamental status of his principles—not absolutely, of course, but in the context of what was then known about the electrodynamics of moving bodies—by starting from the definition of simultaneity, in which the invariance of the velocity of light plays a constitutive role. It is within

[9] The constructive interpretation of relativity is expressed in Brown (2005). For opposing views, see Norton (2008) and Janssen (2008).

this kinematical framework—constituted, however, by a link between kinematics and dynamics through the light-principle—that the dynamical theory of Lorentz is reconstructed. In order to give a constructive account of this same framework, one would need to reconstruct Einstein's principles within some (putatively) more fundamental framework, whose constitutive principles do not presuppose those of Einstein's theory. The lack of such a constitutive principle, as we've already seen, was a central conclusion of Einstein's conceptual analysis.

To motivate a constructive account, Brown (2005) argues that the kinematical relations expressed by special relativity stand in need of dynamical explanation, as exemplified by the case of the Lorentz contraction. If relativity is taken as a principle theory, this is regarded as a purely kinematical effect, but in fact it is a dynamical effect: it is brought about by the behavior of the molecular forces that maintain a body's configuration, which by hypothesis are Lorentz-invariant forces. He appeals to a famous example of J.S. Bell, in which two rockets, joined by a string, undergo identical accelerations; according to Bell, the Lorentz contraction of the string will eventually cause the string to break (Bell 1993).[10] Brown regards this as showing that the contraction is evidently a dynamical effect, in need of a dynamical explanation, and appeals to a moral from Bell: even if Einstein's theory gives a kinematical derivation of the contraction, "you are not excused from seeing how the detailed dynamics of the system also leads to the Fitzgerald contraction" (quoted in Brown 2005, pp. 125–126).

One may take Bell's moral to be a reminder that the configuration of a "rigid" body is a complicated matter, involving the theory of the forces binding its particles together. It sounds reasonable to say that, in a Lorentz invariant theory, the body's length contracts because it is held together by Lorentz-invariant forces. But this is not really a dynamical explanation of the contraction, which remains a frame-dependent effect; there is, after all, a physically equivalent reference frame in which the effect does not occur. It is only a dynamical phenomenon within the framework of Lorentz's assumptions about time and space: if a body has an objective length, and an objective state of motion with respect to the ether, then its contraction while in motion must be a dynamical effect of that motion on the forces that are responsible for its configuration. Lorentz himself pointed out that the contraction hypothesis becomes a plausible one,

> as soon as we assume that molecular forces are also transmitted through the ether, like the electric and magnetic forces of which we are able at the present time to make this assertion definitely. . . . Now, since the form and dimension of a solid body are ultimately conditioned by the intensity of molecular actions, there cannot fail to be a change of dimensions as well. (Lorentz 1952, p. 6)

But if simultaneity is relative, then the body does not have an objective length, and in fact there is no objective framework within which such a dynamical explanation can be constructed.

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10 See Bub and Pitowsky (2010) for a useful discussion of this problem.

Perhaps some confusion is built into the formulation of the problem, specifically as a question about the contraction of a body, and therefore about the behavior of its internal forces in motion. But the principle of the Lorentz contraction, on Einstein's analysis, is not fundamentally about bodies, but about length as a theoretical concept and the empirical criteria for applying it, in a context in which there is no frame-independent measure of simultaneity. Given two free particles moving in parallel inertial trajectories, the spatial interval between them, in their own plane of simultaneity, will appear contracted in relatively moving frames, and there is obviously no dynamical effect to explain. If they are joined by a string, the contraction of the string with respect to other frames will not require any different explanation. And if the entire system is accelerated in such a way as to break the string, the dynamical explanation will have to do with the induced relative motions of its parts, and the resulting strain on the forces holding them together, but not specifically with the Lorentz contraction; whatever the Lorentz contraction does to the string, it must do equally to the spatial interval that the string is required to span. This, at least, is how the situation must appear from the perspective of Einstein's principle theory as I have characterized it, on the basis of the conceptual criteria that it imposes on specific theories formulated within its constraints.

From this perspective we can also begin to address the challenge implied by the title of Brown and Timpson (2006): "Why special relativity should not be a template for a fundamental reformulation of quantum mechanics." The authors argue that Einstein himself was deeply dissatisfied with the representation of special relativity as a principle theory, and accepted it only provisionally, in the hope that its kinematical principles would eventually yield to some constructive dynamical explanation.[11] On this view, the constraint that the theory imposes on other theories is a purely phenomenological one. If the fundamental constraint is a conceptual one, however, then the kinematical presuppositions of other theories must have an empirical reconstruction in accord with the criteria identified by Einstein, and in particular those presuppositions must not depend on unwarranted assumptions about simultaneity. In short, Einstein's (1905) interpretation of special relativity provides a template for the reformulation of mechanics, provided that the task of reformulation is construed precisely as a task of interpretation—within the constraints imposed by a conceptual analysis after the pattern of Einstein's – rather than a task of reconstructing the principles of quantum mechanics within some deeper explanatory framework. The difficulty of interpreting quantum mechanics reflects, at least in part, the severity of the task that such a template sets. It is not sufficient to identify a limit on the applicability of certain concepts, and to give that limit the status of a fundamental principle, as in Einstein (1905) or Heisenberg (1927). It must also be shown that the same conceptual analysis leads to a principle on which a theoretical framework can be constructed. In other words, the framework that succeeds in providing a uniquely natural interpretation of quantum mechanics must provide, not only an argument that no classical account of the state of a physical system is available, but also an

[11] See also Brown (2005), chapter 5.

argument for the uniqueness of the principle that it identifies as the core of the principle theory of quantum mechanics. The invariance of the velocity of light and the resulting definition of simultaneity can claim to be central and indispensable both to the critical analysis of Newtonian kinematics, and to the relativistic reconstruction of electrodynamics. It remains to be seen whether any particular framework for the reconstruction of quantum mechanics as a principle theory can make a similarly compelling claim.[12]

1.4 Structure and Interpretation

Understanding the role of conceptual analysis in the construction of theories leads to some insight into broader questions of interpretation. Evidently it provides an alternative to the logical positivists' view of the relation between theory and observation, according to which theories are uninterpreted formal structures, and theoretical terms are linked to observations by correspondence rules or coordinative definitions. In place of the conventional assignment of empirical meaning by those means, conceptual analysis finds the interpretation of a theoretical concept by an investigation of the presuppositions under which it is used in some practice of scientific reasoning. The interpretation is justified not only a posteriori by the pragmatic value of the framework that it helps to define, but also a priori—in a relative and contingent sense—by its success in capturing the essential content of those presuppositions and the roles that they play in the theoretical framework as a whole.[13] But one might pose the problem of interpretation in a different way. On the semantic view of theories, since a theory is represented model-theoretically as a formal structure, its empirical interpretation consists in having "the world" as one of its models. In this setting, the positivists' problem of interpretation does not appear. Therefore Reichenbach or Carnap would undoubtedly wish to ask what it could mean to say that "the world" is or is not a model of, say, Euclidean geometry—unless or until some stipulation is adopted that identifies something in the observable world as representing some key theoretical notion, such as the path of a light ray as a straight line. Such questions are not addressed directly by the "constructive empiricist" version of the semantic view (cf. van Fraassen 1980), which is distinguished by its focus on empirical adequacy instead of truth, so that a theory is required to have, not the world, but the phenomena, as a model. It was Demopoulos (2003) who pointed out that these views, constructive empiricism included, are subject to a criticism that was first raised against Russell's structuralism: the claim that a structure has the world as one of its models, or even has only the set of all phenomena as one of its models, is essentially trivial. The existence of an isomorphism between a model of the theory and the domain of phenomena depends only the cardinality of

[12] See Chapter 12, this volume, and Demopoulos (2011a).

[13] See DiSalle (2002) for further discussion of the contrast between the view presented here and the views of the logical positivists.

the domain.[14] In short, the problem of interpreting theories cannot be seen any more clearly from the semantic view.

Van Fraassen, taking account of Demopoulos's criticism, recently expressed the predicament, the "basic perplexity," in which these considerations place his constructive empiricist project:

> What does it mean to embed the phenomena in an abstract structure? Or to represent them by doing so?... Hence the most fundamental question is this: How can an abstract entity, such as a mathematical structure, represent something that is not abstract, something in nature? (2008, p. 234)

This is not the place for an assessment of van Fraassen's attempt to address this predicament. It is worthwhile, however, to consider the problem in light of further remarks by Demopoulos on conceptual analysis. Van Fraassen's perplexity starts from the idea that the mathematical representation of the world, understood as a formal relation between the mathematical structure and the phenomena, begs the main question: a mathematical structure can represent the phenomena only on the assumption that the latter, too, already have a mathematical representation. Demopoulos notes, however, that between mathematics and the world of phenomena there is a domain of *conceptual* representation:

> any reasonable formulation of the problem of how mathematics represents reality must be predicated on the assumption that we can provisionally take for granted what is meant by *conceptually representing* reality, and that we can also take for granted that a conceptual representation does not reduce to or presuppose a *mathematical* representation. Otherwise we would be forced to reject Frege's celebrated solution to the problem of how arithmetic *applies* to reality. For Frege, this is explained by the fact that our judgments of cardinality rest on relations between concepts, and concepts sometimes apply to reality. (Demopoulos 2011b)

Demopoulos' discussion concerns the foundations of arithmetic, but considering it in the broader context of applied mathematics, we are led to agree that the problem of representation is misleadingly posed.

Consider the problem of physical geometry: what is meant by the question whether some particular geometrical structure is a correct representation of the world, or more modestly, of the phenomenal world? This is clearly not a question of how to determine an isomorphism between an abstract structure and a concrete collection of objects. That is, the question is not, strictly, how the formal structure corresponds to the world or to the phenomena, but how well the structure captures *our space*. But our space—not in itself, whatever that may mean, but inasmuch as it is an object of our knowledge, and a candidate for theoretical knowledge in the first place—is already constituted as a conceptual scheme, beginning with the primitive group-theoretic conception identified by Poincaré as the basis of our elementary spatial knowledge. To whatever degree that our observations are capable of being represented in a series of increasingly complicated geometrical structures,

[14] For further discussion and context, see also Demopoulos and Friedman (1985).