QUANTUM INFORMATION THEORY
& the Foundations of Quantum Mechanics

CHRISTOPHER G. TIMPSON

OXFORD

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Christopher G. Timpson

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PREFACE

This book is an essay in conceptual analysis: the analysis of one of the most prominent and exciting new areas of physics—quantum information theory. Quantum information is a field at the intersection of quantum physics, communication theory and computer science. It has considerably increased our understanding of quantum mechanics, developed our conception of the nature of computation, and spurred impressive increases in our ability to manipulate and control individual quantum systems. Not only that, but the theory hints enticingly at ideas of rich philosophical promise.

My aim here, first of all, is to carve out an understanding of the nature of information and particularly, of quantum information, which will allow us to gain a clear view of what quantum information theory is all about. The account I give of the concept of quantum information allows us to resolve various puzzles internal to the theory, concerning the nature of nonlocality and information flow in the presence of entanglement; and it provides us with a better grasp of the relation between quantum information theory and the world. This in turn permits a clear view of what the ontological and methodological lessons provided by quantum information theory are; lessons which bear on the gripping question of what role a concept like information has to play in fundamental physics.

My second (but not secondary!) aim is to assess the claim that advances in quantum information theory pave the way for the resolution of the traditional conceptual problems of quantum mechanics; roughly speaking, the deep problems which loom over measurement and the issue of entanglement and nonlocality; more generally, the puzzles about what the quantum world is *like*. Being clear to begin with on the notion of information renders this task of assessment considerably more manageable. I critically assess a number of the concrete proposals which have been offered. One moral which will be drawn is that there are no *cheap* resolutions of the traditional problems to be had: various of the approaches, whatever other merits they may have, leave these problems untouched. And even then, there is still considerable work to be done. The deepest lessons, perhaps, are still waiting to be learnt; but I trust that we will be better placed to appreciate them having trodden the path that I lay out here.

A note on the genesis of this work: this book is a development of my 2004 DPhil thesis of the same title (Timpson, 2004*b*). Some matters of a more narrowly technical interest included there have been excised and a good deal of material revised and added. The discussion of the nature of information (Chapters 2 and 3 of the present work) has been considerably extended and developed; in particular, the positive account of the nature of quantum information which was only implicit in the 2004 thesis receives a full treatment here. The most notable addition (filling the most obvious previous lacuna) is the discussion of quantum Bayesianism (Chapters 9 and 10). A slightly shortened version of this material appeared as 'Quantum Bayesianism: A Study', *Studies in the History and Philosophy of Modern Physics*, **39**(3), 579–609 (2008), published by Elsevier. I thank the UK Arts and Humanities Research Council for a research leave award and the Department of Philosophy at the University of Leeds for additionally providing matching leave, which together enabled me to spend a good deal of the academic year 2006–7 working on this material. Chapters 4 and 5 have previously been published as, respectively, 'The Grammar of Teleportation', *British Journal for the Philosophy of Science*, **57**(3), 587–621 (2006) (Oxford University Press) and 'Nonlocality and Information Flow: The Approach of Deutsch and Hayden', *Foundations of Physics*, **35**(2), 313–343 (2005) (Springer). They appear here with minor amendments. Part of Chapter 6 is a much revised version of part of Timpson (2004*a*).

It is my pleasant duty to record here a goodly number of further thanks. My main intellectual debts are to my former teachers, now colleagues and friends, John Hyman and Harvey Brown. This book would not be at all as it is (more probably: simply would not be) without their respective influences. In addition I should particularly mention Jon Barrett, Chris Fuchs, Jeff Bub, Jeremy Butterfield, Antony Valentini and Jos Uffink for their help and support. Thanks are also due to a large number of friends and colleagues at Oxford and elsewhere, including Marcus Appleby, Katherine Brading, Guido Bacciagaluppi, Carl Caves, Ari Duwell, Doreen Fraser, Steven French, Alexei Grinbaum, Hans Halvorson, Michael Hall, Leah Henderson, Clare Horsman, Richard Jozsa, Pieter Kok, James Ladyman, Matt Leifer, Owen Maroney, Peter Morgan, Wayne Myrvold, Michael Nielsen, Oliver Pooley, Greg Radick, Alastair Rae, Simon Saunders, Rüdiger Schack, Nick Shea, Michael Seevink, Mauricio Suarez, Rob Spekkens and Mark Sprevak. David Wallace and Joseph Melia have both been particularly influential on my thinking. I must thank my editor at OUP, Peter Momtchiloff, above all for his remarkable patience.

This book is intended to be of interest both to physicists and to philosophers concerned with the conceptual standing and implications of quantum information theory. Accordingly I have made some effort to define my terms and to explain what may be unfamiliar as I go along (though there is much to get through, so the pace perhaps remains unfortunately quick at times). The book is also intended to be accessible to advanced undergraduates in either field. However, a good grasp of the quantum mechanical formalism is presupposed throughout. In case that should constitute a bar, an appendix reviewing the elements of the quantum formalism is provided. A more serious presupposition, perhaps, is a fair degree of familiarity—at least in outline—with the standard foundational debates in quantum mechanics: the problem of measurement, debates surrounding the nature of entanglement and quantum nonlocality, the pros and cons of the standard interpretations of quantum theory. Much of interest would be gained by following up the various references I cite in the course of the discussion, but if this area were unfamiliar and pointers needed, one might turn to Albert (1992), before moving on to Redhead (1987), Bub (1997), and Wallace (2009).

This book is dedicated to my wife Jane and daughter Catherine. Quite apart from everything else, Jane was kind enough to make the figures.

CGT
Brasenose College,
Oxford

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INTRODUCTION

Much is currently made of the concept of information in physics, following the rapid growth of the fields of quantum information theory and quantum computation. These are new and exciting fields of physics whose interests for those concerned with the foundations and conceptual status of quantum mechanics are manifold. On the experimental side, the focus on the ability to manipulate and control individual quantum systems, both for computational and cryptographic purposes, has led not only to detailed realization of many of the *gedanken*-experiments familiar from foundational discussions (cf. Zeilinger, 1999*a*, for example), but also to wholly new demonstrations of the oddity of the quantum world (Boschi *et al.*, 1998; Bouwmeester *et al.*, 1997; Furusawa *et al.*, 1998). Developments on the theoretical side are no less important and interesting. Concentration on the possible ways of using the distinctively quantum mechanical properties of systems for the purposes of carrying and processing information has led to considerable deepening of our understanding of quantum theory. The study of the phenomenon of entanglement, for example, has come on in leaps and bounds under the aegis of quantum information (see, e.g., Bruss (2002) for a useful review of developments).

The excitement surrounding these fields is not solely due to the advances in the physics, however. It is due also to the seductive power of some more overtly philosophical (indeed, controversial) theses. There is a feeling that the advent of quantum information theory heralds a new way of doing physics and supports the view that information should play a more central role in our world picture. In its extreme form, the thought is that information is perhaps the fundamental category from which all else flows (a view with obvious affinities to idealism), and that the new task of physics is to discover and describe how this information evolves, manifests itself, and can be manipulated. We can call this kind of view, which would do away with material items like particles and fields at the fundamental physical level and replace them with an immaterial basis of information, *informational immaterialism*. The best known proponent of such an idea is perhaps the late John Wheeler with his infamous 'It from Bit' proposal, the idea that every physical thing (every 'it') derives its existence from the answer to yes–no questions posed by measuring devices:

> No element in the description of physics shows itself as closer to primordial than the elementary quantum phenomenon ... in brief, the elementary act of observer participancy ... It from bit symbolizes the idea that every item of the physical world has at bottom—at a very deep bottom, in most instances—an immaterial source and explanation; that which we call reality arises in the last analysis from the posing of yes–no questions that are the registering of equipment evoked responses; in short that all things physical are information-theoretic in origin and this is a *participatory universe*. (Wheeler, 1990, pp. 3, 5)

Less extravagantly, we have the ubiquitous, but baffling, claim that 'Information is Physical' (Landauer, 1996) and the widespread hope that quantum information theory will have something to tell us about the still vexed questions of the interpretation of quantum mechanics.

These claims are ripe for philosophical analysis. To begin with, it seems that the seductiveness of such thoughts appears to stem, at least in part, from a confusion between two senses of the term 'information' which must be distinguished: 'information' as a technical term which can have a legitimate place in a purely physical language, and the everyday concept of information associated with knowledge, language, and meaning, which is completely distinct and about which, I shall suggest, physics has nothing to say. The claim that information is physical is baffling, because the everyday concept of information is reliant on that of a person who might read or understand it, encode or decode it, and makes sense only within a framework of language and language users; yet it is by no means clear that such a setting may be reduced to purely physical terms; while the mere claim that some physically defined quantity (information in the technical sense) is physical would seem of little interest. The conviction that quantum information theory will have something to tell us about the interpretation of quantum mechanics seems natural when we consider that the measurement problem is in many ways the central interpretive problem in quantum mechanics and that measurement is a transfer of information, an attempt to gain knowledge. But this seeming naturalness only rests on a confusion between the two meanings of 'information'.

My aim in this study is to make progress with these and other puzzles; and the first step is to achieve clarity on the nature of quantum information theory. The key to that, in turn, is getting clear on the concept of information; and in particular, on the concept of *quantum* information. Many have found this concept rather opaque and puzzling: needlessly so, I shall argue.

It is commonly supposed that the straightforward question 'What is quantum information?' has not yet received—and perhaps cannot be expected to receive—a definite or illuminating answer. Compare the Horodeckis:

> Quantum information, *though not precisely defined*, is a fundamental concept of quantum information theory. (Horodecki *et al.*, 2006)

And Jozsa:

> $|\psi\rangle$ may be viewed as a carrier of 'quantum information' which ... we leave ... undefined in more fundamental terms ... Quantum information is a new concept with no classical analogue ... In more formal terms, we would aim to formulate and interpret quantum physics in a way that has a concept of information as a primary fundamental ingredient. Primary fundamental concepts are *ipso facto* undefined (as a definition amounts to a characterization in yet more fundamental terms) and they acquire meaning only afterward, from the structure of the theory they support. (Jozsa, 2004)

But I shall argue that we can do rather better than this: the concept of quantum information can be laid quite plain and bare before us. It can be straightforwardly defined (it is not a primitive) and a simple account may be given of the ontological status of quantum information. When a proper understanding of the significance of the coding theorems is in place, it can be seen (*pace* Jozsa and his Hilbertian analysis above) that quantum information and classical Shannon information are more than analogous: they are species of a single genus.

The account I will go on to provide of the nature of quantum information is ontologically deflationary. We should not take the view that information in general, nor quantum information in particular, is any kind of physical substance or stuff—even if a very nebulous and aethereal one—as the writings of some authors might lead us to suppose. But neither should we take the nihilist view that quantum information does not exist. The middle way—the right way—is to pay careful attention to the logical status of the concept of information. It proves essential to recognize that 'information' is an abstract noun: then we can see clearly what information talk is doing, both in the quotidian and in the quantum context.

Before we can begin to make these helpful steps towards understanding the concept of quantum information, however, we need to be sure that we are starting off on the right foot, with a proper understanding of the familiar Shannon concept. Now discussions of information theory, both quantum and classical, generally begin with an important caveat concerning the scope of their subject matter. These warnings typically take some such form as this:

> Note well, reader: Information theory doesn't deal with the *content* or *usefulness* of information, rather it deals only with the *quantity* of information.[1]

But while there is obviously an important element of truth in statements such as these, they can also be seriously misleading, in two interrelated ways. First, the distinction between the technical notions of information deriving from information theory and the everyday semantic/epistemic concept is not sufficiently noted;[2] for it may easily sound as if information theory does at least describe the *amount* of information in a semantic/epistemic sense that may be around. But this is not so. In truth we have two quite distinct concepts (or families of concepts)—the everyday and the technical—and quantifying the amount of the

[1] Examples of the disavowals—Weaver: '... *information* must not be confused with meaning. In fact, two messages, one of which is heavily loaded with meaning and the other of which is pure nonsense, can be exactly equivalent from the present viewpoint as regards information' (Shannon and Weaver, 1963, p. 8). Similarly Feynman: '... "information" in our sense tells us nothing about the usefulness or otherwise of the message' (Feynman, 1999, p. 118); and Cherry: 'It is important to emphasise, at the start, that we are not concerned with the meaning or truth of messages; semantics lies outside the scope of mathematical information theory' (Cherry, 1951, p. 383).

[2] Bar-Hillel (1955) is an early and an exemplary entreaty not to confuse the information theory notion of information with information proper. Bar-Hillel also notes, with chagrin, the tendency of authors to backslide once they get beyond their opening disavowals; I share his sense of regret.

latter does not tell us about the quantity, if any, of the former (a claim which would be no surprise to Shannon himself, in fact (Shannon, 1948, p. 31)). The second point of concern is that the coding theorems that introduced the classical (Shannon, 1948) and quantum (Schumacher, 1995) concepts of information do not *merely* define measures of these quantities. They also introduce the concept of *what it is* that is transmitted, of *what it is* that is measured. Thus we may as happily describe what information in the information-theoretic setting is, as how much of it there may be. It is this which opens the door to a general definition of what information in a Shannon-style information theory is; and the consequent—clarifying—recognition that quantum information falls under this general definition.

Thus I begin in Chapter 2 by addressing the general question 'What is information?' The shape of the issues is cleanest if one transposes this question immediately into the formal mode: 'How does the term "information" behave?' This highlights various features of the everyday notion, specifically, that 'information' is an abstract noun whose function is to be explained in terms of the conceptually simpler verb 'inform'; which is in turn to be explained by appeal to the concept of knowledge. I draw a distinction between possessing and containing information; and I indicate the lines of difference between the everyday concept and Shannon's technical one. Various philosophical terms of art—and more importantly, the distinctions they mark—are then introduced: distinctions between sentence and statement (proposition); between sentence type and sentence token; between type and token more generally; and finally between object and property. These distinctions prove essential to appreciating the ontological status of information. We then turn to the Shannon concept and I provide a general definition of what information in a Shannon-style theory is.

It is easy to come away from standard presentations of the Shannon theory with the wrong impression. Thus some of the claims I shall make about it may sound surprisingly revisionary: the Shannon concept of information is not at all to do with uncertainty; and neither is it centrally concerned with correlation. Neither uncertainty nor correlation provides the key to the Shannon *concept*. (One is not helped by overtones of the everyday concept sliding in here.) Instead what is crucial is the abstract characterization of information sources and the requirement that what is produced by a source be reproducible at the far end of a communication system. The quantitative side of the Shannon theory is concerned purely with specifying the resources required to achieve this task of transmission. The quantitative concept of Shannon information is then just that of the degree of compressibility of the output of a source: what channel resources are required to transmit the message? What is produced—the piece of Shannon information to be transmitted—we will see to be a particular kind of sequence of states; an abstract item. Thus it transpires that 'information' in the Shannon theory is an abstract noun just as much as it is in the everyday context. I close the chapter with a brief discussion of Dretske's attempt to base a semantic notion of information on ideas from information theory; I argue that this attempt is not successful.

In Chapter 3 the approach to thinking about information developed in the previous chapter is turned towards the quantum theory. First, some of the characteristic ideas and applications of quantum information theory are presented: bits versus qubits; accessible versus specification information; the Holevo bound; the no-cloning theorem; the use of entanglement to assist communication; the examples of superdense coding and teleportation; a brief sketch of the notion of quantum computation. Then comes the core of the chapter (Section 3.6): the discussion of the nature of quantum information. With the correct conception of Shannon information to hand, the dimension of generalization which the quantum concept occupies becomes clear. Quantum information is simply what is produced by a quantum information source. As in the classical case, a piece of quantum information will be an abstract type (in fact a sequence of quantum states), rather than some kind of concrete thing or physical substance. This conception is defended from a number of potential objections which might be raised. With a clear grasp obtained of the relation between quantum information and the world, it proves short work to dissect the slogan 'Information is Physical' and dispatch the prospect of informational immaterialism (Section 3.7.1).

Chapter 4 is a case study whose purpose is to illustrate the value of recognizing clearly the logico-grammatical status of the term 'information' as an abstract noun: in this chapter I investigate the phenomenon of quantum teleportation in detail. While teleportation is a straightforward consequence of the formalism of non-relativistic quantum mechanics, it has nonetheless given rise to a good deal of conceptual puzzlement. I illustrate how these puzzles generally arise from neglecting the fact that 'information' is an abstract noun. When one recognizes that 'the information' does not refer to a concrete particular or to some sort of pseudo-substance, any puzzles are quickly dispelled. The central moral is that one should not be seeking, in an information-theoretic protocol—quantum or otherwise—for some particular 'the information', whose path one is to follow, but rather concentrating on the physical processes by which the information is transmitted, that is, by which the end result of the protocol is brought about. When we bear this in mind for teleportation, we see that the only remaining source for dispute over the protocol is the straightforward one regarding what interpretation of quantum mechanics one wishes to adopt. I go on to describe how teleportation looks within a number of familiar interpretations.

Chapter 5 continues the theme of the preceding chapter. In it I discuss the important paper of Deutsch and Hayden (2000), which would appear to have significant implications for the nature and location of quantum information: Deutsch and Hayden claim to have provided an account of quantum mechanics which is particularly local, and which finally clarifies the nature of information flow in entangled quantum systems. I provide a perspicuous description of their formalism and assess these claims. It proves essential to distinguish, as Deutsch and Hayden do not, between two ways of interpreting their formalism. On the first, conservative, interpretation, no benefits with respect to locality accrue that are not already available on either an Everettian or a statistical interpretation;

and the conclusions regarding information flow are equivocal. The second, ontological, interpretation, offers a framework with the novel feature that global properties of quantum systems are reduced to local ones (this is an extremely striking result); but no conclusions follow concerning information flow in more standard quantum mechanics. We see in particular that the Deutsch–Hayden approach does not provide us with a novel account of the nature of quantum information or of how quantum information behaves.

Chapter 6 is a discussion of some of the philosophical questions raised by the theory of quantum computation. First I consider whether the possibility of exponential speed-up in quantum computation provides an argument for a more substantive notion of quantum information than I have previously allowed, concluding in the negative, before moving on to consider some questions regarding the status of the Church–Turing hypothesis in the light of quantum computation. In particular, I argue against Deutsch's claim that a physical principle, the Turing Principle, underlies the Church–Turing hypothesis; and consider briefly the question of whether the Church–Turing hypothesis might serve as a constraint on the laws of physics.

In Chapter 7 we change tack and turn our attention directly towards the question of the foundations of quantum mechanics. Whether advances in quantum information theory will finally help us to resolve our conceptual troubles with quantum mechanics is undoubtedly the most intriguing question that this new field holds out. Interestingly, such diametrically opposed interpretational viewpoints as Copenhagen and Everett have both drawn strength since its development. Copenhagen, because appeal to the notion of information has often loomed large in approaches of that ilk; and a quantum theory of information would seem to make such appeals more serious and precise (more scientifically respectable, less hand-waving); Everett, because the focus on the ability to manipulate and control individual systems in quantum information science encourages us to take the quantum picture of the world seriously; because of the intuitive appeal of a parallel-processing-in-many-worlds view of quantum algorithms (a view due to Deutsch); and most importantly, because of the theoretical utility of always allowing oneself the possibility of extending a process being studied to a unitary process on a larger Hilbert space.[3] In addition to providing meat for interpretational heuristics, quantum information theory, with its study of quantum cryptography, error correction in quantum computers, the transmission of quantum information down noisy channels, and so on, has given rise to a range of powerful analytical tools that may be used in describing the behaviour of quantum systems and therefore in testing our interpretational ideas.

In this chapter, however, my intention is merely to set out some simple preliminaries that are needed to guide us when investigating what work appeal to the concept of information might do for the foundations of quantum mechanics. One point noted is that if all that appeal to information were to signify in a

[3]This is known in the trade as belonging to the Church of the Larger Hilbert Space.

given approach is the advocacy of an instrumentalist view, then we would not be left with a very interesting, or at least, not a very distinctive, position. Another is the warning that the factivity of 'information' (one can't have the information that p unless it is the case that p) tightly constrains what a direct appeal to the notion of information can do for you in understanding the quantum state.

The most prominent lines of research engaged in bringing out implications of quantum information theory for the foundations of quantum mechanics have been concerned with establishing whether information-theoretic ideas might finally provide a perspicuous conceptual basis for quantum mechanics, perhaps by suggesting an axiomatization of the theory that lays our interminable worrying to rest. That one might hope to make progress in this direction is a thought that has been advocated persuasively by Fuchs (2003), for example. In Chapter 8, I investigate some proposals in this vein, in particular, Zeilinger's Foundational Principle and the information-theoretic characterization theorem of Clifton, Bub and Halvorson (Clifton *et al.*, 2003). I show that Zeilinger's Foundational Principle (*'An elementary system represents the truth value of one proposition'*) does not in fact provide a foundational principle for quantum mechanics and fails to underwrite explanations of the irreducible randomness of quantum measurement and the existence of entanglement, as Zeilinger had hoped. The assessment of the theorem of Clifton, Bub and Halvorson is more positive: here indeed an axiomatization of quantum mechanics has been achieved. However, I raise some questions—as others have too—concerning the C^*-algebraic starting point of the theorem. It seems that this is not a sufficiently neutral theoretical framework for the axiomatic project. Moreover, I argue that far from the Clifton–Bub–Halvorson result motivating an information-theoretic approach (or so-called *principle theory* approach) to understanding the quantum world which obviates our traditional conceptual concerns, such an approach simply fails to engage with the crucial interpretational issues.

The final proposal we shall consider—in Chapters 9 and 10—is perhaps the most radical. It is the *quantum Bayesianism* of Caves, Fuchs and Schack. This approach is dramatic in its starting point, which is to insist that all probabilities, even those encapsulated in a quantum state assignment, are entirely subjective (in the subjective Bayesian sense); merely matters of the degrees of belief that an agent might have, rather than of how things are. The thought is that once the correct view of the quantum state and related structures is adopted—i.e., the subjective Bayesian view—it will be possible to find within the quantum formalism the real ontological truths it is trying to teach us. Using the techniques of quantum information theory, the aim is to separate the chaff of the subjective elements of the formalism (to do with our reasoning) from the wheat: the objective features of the theory which reflect physical facts about the world. In Chapter 9 I begin by presenting and motivating the approach in some detail, before defending it from various common objections; while in Chapter 10 I present some more substantive challenges which the approach faces. The conclusions are mixed. In many ways, quantum Bayesianism represents the *acme* of certain traditional ways of thinking about quantum mechanics (broadly speaking, Copenhagen-inspired ways). If one hopes to defuse the conceptual troubles over collapse and nonlocality by conceiving of the quantum state in terms of some cognitive state, then the only satisfactory way to do so is by adopting the quantum Bayesian line. Moreover, the quantum Bayesians do not rest at the stage of merely providing an (admittedly highly contentious) interpretation of the quantum formalism; they seek to go further and explain *why it is* that the world has to be construed that way. Now, the latter task, we must grant, is a research programme rather than a *fait accompli*, but as things stand, the quantum Bayesian faces difficulties in providing a satisfactory account of explanation in the quantum realm and over the question of whether subjective probabilities are really adequate; or so I shall argue.

Where do these deliberations leave us? It is useful to distinguish between two general kinds of strategies which have been manifest in attempts to obtain philosophical or foundational dividends from quantum information theory: the direct and the indirect. The direct strategies include such thoughts as these: the quantum state is to be understood as information; quantum information theory supports some form of immaterialism; quantum computation is evidence for the Everett interpretation; information is to be thought of as some new kind of physical entity which provides a subject matter for quantum mechanics. None of these proposals survives close examination; and it seems unlikely that any such direct attempt to read a philosophical lesson from quantum information theory will. Much more interesting and substantial are the indirect approaches which seek, for example, to learn something useful about the structure or axiomatics of quantum theory by reflecting on quantum information-theoretic phenomena; that might look to quantum information theory to provide new analytic tools for investigating that structure; or that look to suggested constraints on the power of computers as potential constraints on new physical laws. In these directions, there may be much to be learnt.

A general methodological moral suggests itself too. *Disunity* is a prominent theme in current philosophy of science: the failure of the dream (or illusion?) of positivist unified science; the explanatory (and perhaps nomological?) autonomy of various sections of scientific knowledge; the sheer diversity displayed across the range of scientific endeavour. Presented with this dauntingly diverse landscape, it is natural to seek for concepts which may nonetheless deploy some kind of unifying power across this disparate range; and for many *information* naturally presents itself as just such a concept. It seems to be employed fruitfully in very many different areas, from linguistics to cognitive science, from biology to computer science, from engineering to thermodynamics, statistical mechanics and quantum physics. Surely information is a natural candidate to provide high-level unification[4] across these and other areas? Well, the results of our investigations here should give us pause. To make sense of the field of quantum

[4]As opposed to the dream of *reductive* unification.