Information, Immaterialism, Instrumentalism: Old and New in Quantum Information[*]

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We live, we are told, in an information age. We are told this, perhaps, less often than once we were; but no doubt only because the phrase has become worn from use. If ours is an age of information, then quantum information theory is a field propitiously in tune with the spirit of the times: a rich and sophisticated physical theory that seeks to tame quantum mysteries (no less!) and turn them to ingenious computational and communication ends. It is a theory that hints, moreover, at the possibility of finally rendering the quantum *unmysterious*; or at least, this is a conclusion that many have been tempted to draw.

And yet, for all its timeliness, some of the most intriguing of the prospects that quantum information science presents are to be found intertwining with some surprisingly old and familiar philosophical themes. These themes are immaterialism and instrumentalism; and in this essay we shall be exploring how these old ideas feature in the context of two of the most tantalizing new questions that have arisen with the advent of this field: Does quantum information theory finally help us to resolve the conceptual conundrums of quantum mechanics? And does the theory indicate a new way of thinking about the world—one in which the material as the fundamental subject matter of physical theory is seen to be replaced by the immaterial: information?

The moral I will suggest is that it is only once the influence of these old ideas is explicitly recognised for what it is and treated accordingly that one can begin to hope

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for genuine new insights stemming from quantum information theory. Shannon, in the 1950s, warned against uncritical appeal to the concept of information (Shannon, 1956). We do well to heed his warning now.

1 Two thoughts

Why do our two tantalizing questions arise? Why should one think that quantum information theory—a branch of quantum mechanics intersecting with computer science and communication theory—might have any particular philosophical consequences in the first place? There are a number of reasons[1], but the two most central to our concerns might be introduced in the following way.

Let us call the thought that information might be the basic category from which all else flows *informational immaterialism.* On this view, the new task of physics, foreshadowed in the development of quantum information theory, will be to describe the various ways in which information can evolve and manifest itself. Why might one be led to such a view? The thought could be as straightforward as this: We now have a fundamental—that is to say, a quantum—theory of information; so perhaps the fundamental theory of the world could just be about information (immaterial) rather than about things (material)[2].

Wheeler, with his 'It from Bit' proposal is the cheerleader for this sort of view (It = physical thing; bit = information):

> 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 very deep bottom, in most instances—an immaterial source and explanation; that which we call reality arises in

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[1] See Timpson (2008a) for an introduction to the theory that seeks to emphasise various issues of philosophical interest.

[2] I make no claim that this is a good argument. Far from it. But it does seem to represent at least one strand of thought—largely unarticulated, perhaps—operative amongst those pursuing these idealist lines. Notice that it equivocates between two senses of the term 'information'. 'Information' as a technical term introduced by an information theory, quantum or classical; and 'information' as the everyday semantic/epistemic term. These are importantly distinct (see Timpson (2004, 2008b,a) for discussion). To be the grounds for an immaterialist metaphysics 'information' will need to refer to the semantic/epistemic concept: pieces of information would be the correlate—in modern terminology—of good old sense data. But 'information' as it features in information theory has no direct link to any semantic or epistemic concept.

> 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, p.3,5)

Or compare Steane:

> It now appears that information may have a much deeper significance. Historically, much of fundamental physics has been concerned with discovering the fundamental particles of nature and the equations which describe their motions and interactions. It now appears that a different programme may be equally important: to discover the ways that nature allows...*information* to be expressed and manipulated, rather than particles to move. (Steane, 1998, p.120-121)

Finally, Zeilinger:

> So, what is the message of the quantum? I suggest we look at the situation from a new angle. We have learned in the history of physics that it is important not to make distinctions that have no basis—such as the pre-Newtonian distinction between the laws on Earth and those that govern the motion of heavenly bodies. I suggest that in a similar way, the distinction between reality and our knowledge of reality, between reality and information cannot be made. (Zeilinger, 2005)

Mixed in here, in the quotations from Wheeler and Zeilinger, is another important element in the immaterialist drive: strands of Copenhagen thought on the meaning of quantum mechanics. This is something we shall be returning to as we proceed.

The second thought arises perhaps more intuitively. It is very natural to think that the advent of quantum information theory might shed light on the conceptual troubles of quantum mechanics. After all, the *central* problem in quantum mechanics, the problem on which all else turns, is the measurement problem. Yet what is a measurement? Zurek sets the question up nicely[3]:

> Quantum measurements are usually analysed in abstract terms of wavefunctions and Hamiltonians. Only a very few discussions of the measurement problem in quantum theory make an explicit effort to consider the crucial issue—the transfer of information. Yet obtaining knowledge is the very reason for making a measurement. (Zurek, 1990)

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[3] Although beware again of the possibility of equivocation between different senses of the term 'information'.

So a measurement is an attempt to gain knowledge (information). But now we have a *quantum* theory of information: enlightenment is sure to follow! Or so the thought.

So much by way of introduction. We will begin the main discussion by exploring in more detail some of the ways in which it has been argued that appeal to the concept of information will aid our understanding of the basic conundrums in quantum mechanics: specifically the problems of measurement and nonlocality. Hartle (1968) illustrates a common strategy: if the quantum state is understood to represent information rather than an objective feature of the world, our troubles seem to disappear. However I will suggest that this strategy proves problematic. It would seem either tacitly to invoke hidden variables, or to slide into a form of instrumentalism. But instrumentalism is not in itself a particularly edifying interpretive option: if this is all that appeal to information would amount to, we would not have succeeded in articulating a position of any interest. A further problem for the strategy can be noted: the factivity of the term 'information' implies that the objectivity it was the express aim of the approach to avoid is inevitably re-introduced. It follows that if one is to make any progress by associating the quantum state with some cognitive state, it must be the state of belief that is chosen, not that of knowledge.

One might take a different tack. It is possible to avoid the unedifying descent into instrumentalism by focusing instead on the question of whether information-theoretic principles might play the role of providing a perspicuous axiomatic basis for quantum mechanics, as a number of authors have urged (e.g., Fuchs (2003); Clifton et al. (2003)). Here we shall focus on Zeilinger's proposed information-theoretic foundational principle for quantum mechanics (Zeilinger, 1999). His hope is to explain the appearence of intrinsic randomness and entanglement in the theory; and ultimately to answer Wheeler's (1990) question 'Why the quantum?' in a way congenial to the Bohrian intuition that the structure of quantum theory is a consequence of limitations on what can be said about the world. On consideration, however, this approach proves wanting, both formally and conceptually: appeal to the Foundational Principle cannot achieve the results desired.

We will close by exploring in more detail the links between Zeilinger's programme, informational immaterialism and certain strands of Copenhagen thought, specifically the remark infamously attributed to Bohr: 'There is no quantum world'. A good way of understanding what is going on in this remark is by viewing it as an example of semantic ascent. Thus understood, it becomes very clear that moves towards immaterialism are not supported by any such ascent.

2 The quantum state as information

Our two themes are immaterialism and instrumentalism. For better or worse, these are themes that have always been associated, more or less strongly, with the Copenhagen school of thought deriving from Bohr[4]. The notion of information has, in addition, often been appealed to by those working in this tradition. For this reason, Copenhagen-flavoured interpretations have enjoyed something of a renaissance in recent years, on the back of quantum information theory (thereby bucking, to some extent, a contrary trend dating from the late 1960s towards broadly realist philosophies of science), since a quantum theory of information would seem to make such appeals to information more precise, and more scientifically respectable.

The thought typically proceeds by suggesting that far from the central theoretical element of quantum theory—the quantum state—representing how things are in an external, objective world, it merely represents what information one has. Mermin (2001), Peierls (1991), Wheeler (1990) and Zeilinger (1999) have all endorsed this kind of view. Hartle (1968) provides an excellent summary:

> The state is not an objective property of an individual system but is that information, obtained from a knowledge of how a system was prepared, which can be used for making predictions about future measurements.
>
> ...A quantum mechanical state being a summary of the observer's information about an individual physical system changes both by dynamical laws, and whenever the observer acquires new information about the system through the process of measurement. The existence of two laws for the evolution of the state vector...becomes problematical only if it is believed that the

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[4] Needless to say, perhaps, it is very hard to discern any one thing that one might call *the* Copenhagen Interpretation of quantum mechanics. Better to see a pattern of views centred around—and diverging in different ways from—Bohr's own. (For recent studies one might consult Beller (1999); Howard (2004).) And of course, the exact nature of Bohr's own views (neo-Kantian? idealist? entity realist? patch-work realist?) is a matter of controversy. What is undeniable is that he took an instrumentalist view of the quantum formalism itself and had no straightforwardly realist metaphysics.

> state vector is an objective property of the system...The "reduction of the wavepacket" does take place in the consciousness of the observer, not because of any unique physical process which takes place there, but only because the state is a construct of the observer and not an objective property of the physical system. (Hartle, 1968, p.709)

Adopting this approach would seem to transform familiar, difficult, problems into non-problems. We may illustrate with two examples.

Consider one of the common formulations of the measurement problem: Wigner's friend (Wigner, 1961). Here we imagine two scientists, Wigner and friend, one of whom—the friend—is going to perform some quantum experiment and observe its outcome, whilst the other—Wigner—waits outside the (sealed) laboratory, unable to observe proceedings. How should we describe this scenario quantum mechanically? Suppose the experiment is a measurement of the z-component of spin of an electron prepared spin-up in the x-direction. Then the electron's initial state is the superposition:

$$|\psi\rangle_{\text{initial}} = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle), \tag{1}$$

corresponding to no definite value of spin in the z-direction. On performing the measurement, Wigner's friend will see a definite outcome corresponding either to spin-up or to spin-down in the z-direction; accordingly he will assign one of the two spin states $|\uparrow\rangle$ or $|\downarrow\rangle$ to the post-measurement particle, corresponding to a definite z-spin value:

$$|\psi\rangle_{\text{final}} = |\uparrow\rangle, \text{ or } |\psi\rangle_{\text{final}} = |\downarrow\rangle. \tag{2}$$

But how will Wigner describe things? Since the electron-plus-apparatus-plus-friend-plus-lab consitutes a closed physical system, Wigner will describe the evolution of this system unitarily. Thus according to him, the post-measurement state is not one in which the z-spin of the particle is definite, but is one in which the contents of the lab—electron, apparatus and friend all included—is in one big superposition: the initial superposition of the spin is just amplified up to infect everything else:

$$|\Psi\rangle_{\mathrm{lab,final}} = \frac{1}{\sqrt{2}}\big(|\uparrow\rangle_{\mathrm{electron}}|\text{``up''}\rangle_{\mathrm{apparatus}}|\text{sees ``up''}\rangle_{\mathrm{friend}} + |\downarrow\rangle_{\mathrm{electron}}|\text{``down''}\rangle_{\mathrm{apparatus}}|\text{sees ``down''}\rangle_{\mathrm{friend}}\big). \quad (3)$$

Who is right? Does Wigner's friend see a definite outcome, or is he left suspended in limbo until Wigner opens the door to say hello? Do we need to appeal to collapse to reconcile the two views? If so, how, when and why does collapse occur? Why *isn't* Wigner right to treat a closed physical system as unitarily evolving? And so on. These are the familiar kinds of worries[5].

The informational approach aims to undercut this dialectic neatly. The thought is that there need be no disagreement between Wigner and friend. If the quantum state does not represent how things are in the world but what information somebody possesses, then Wigner can assign a state like (3) and his friend can assign one of the states (2) without them thereby making contradictory or contrary statements. They are not disagreeing about how things are, they merely have access to different information—Wigner outside the laboratory and his friend inside. When Wigner gains more information by intrepidly entering the lab, he will update his state accordingly, but as that update does not correspond to a change in anything in the world, it is not a mysterious change, nor one in need of explanation. Thus the argument proceeds.

The second illustrative example is non-locality. Take a familiar EPR scenario: Two parties, Alice and Bob, are spacelike separated and each possess one half of an entangled pair of particles, e.g. one of a pair of spin-half systems in the singlet state:

$$|\psi\rangle_{AB} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_A|\downarrow\rangle_B - |\downarrow\rangle_A|\uparrow\rangle_B). \quad (4)$$

Alice will then perform a measurement on her system. Prior to measurement both Alice

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[5] To recall: Wigner's own view was that one *does* need to invoke a process of collapse, but it is in some sense a partially non-physical process, being brought about by the effect of conscious mind (and not just one's own mind, as Wigner preferred not to conceive solipsistically of his friend hanging in limbo if left to his own devices).

and Bob will assign the maximally mixed state to both of the subsystems of the pair:

$$\rho_A = \rho_B = \frac{1}{2}|\uparrow\rangle\langle\uparrow| + \frac{1}{2}|\downarrow\rangle\langle\downarrow| = \frac{1}{2}\mathbf{1}. \tag{5}$$

The standard story (Einstein et al., 1935) is that the effect of Alice's measurement will be to change the state of Bob's system *instantaneously* and *at a distance*. If she measured in the z-spin basis, for example, obtaining the "up" outcome, the state ascribed to Bob's system will now be $|\downarrow\rangle_B$ rather than $1/2\mathbf{1}$.

Again, the informational approach will suggest that this conclusion of action-at-a-distance is predicated on a false assumption: that the quantum states represent how things are in the world. If they do not, then we no longer have action-at-a-distance. Post-measurement, Alice will assign a different state to Bob's system than he himself does, for example the pure state $|\downarrow\rangle_B$, while he still assigns the mixed state $1/2\mathbf{1}$; but these differences merely represent differences in the information the two possess. The change in the global state from the singlet to the post measurement state $|\uparrow\rangle_A|\downarrow\rangle_B$ (or equivalently the change in the state of Bob's system from $1/2\mathbf{1}$ to $|\downarrow\rangle_B$) does not, on this view, represent a change in the world, a change in Bob's system, but merely an update of Alice's information; *a fortiori* the change does not involve nonlocality. Bob will have no opportunity to update his information about his system until he later meets up with Alice and she reports the outcome of her measurement; but the fact that they assign different states need not mean that they are disagreeing about how the world is.

3 Against 'Information'

So we can see why it might seem appealing to call on the notion of information when trying to make sense of the quantum state. Some thorny problems seem to be dissolved, revealed to be the result of a jejune literalism about the quantum formalism. But things are not really so straightforward. With characteristic perspicacity and concision, John Bell put his finger right on the nub of the central problem with this approach.

'Information' features as one of the bad words on Bell's famous list of terms having 'no place in a formulation with any pretence to physical precision' (Bell, 1990). Why?

Bell indicated the source of his disquiet by posing two questions: if information, then information about *what*? And *whose* information?

I take the first of these to be the most pressing. It presents the informational approach with a troublesome dilemma. If the quantum state represents one's information, there seem to be only two sorts of answer possible to 'Information about what?':

1. Information about what the outcome of experiments will be; or
2. Information about how things are with a system prior to measurement.

Neither of these, I suggest, can happily be adopted by our would-be informationist. Consider answer 2. The information concerns properties of a system which are possessed prior to measurement and which aren't described by the quantum state (in this case because the state doesn't have a world-describing role). What is the more familiar name for such properties? Hidden variables, of course. But recall: the whole point of taking the quantum state as information was to mollify its bad behaviour, its jumping here and there we know not when, its nonlocal collapse. But if to do that we need to introduce hidden variables—to be what it is that the state represents information about—then we are even worse off than we were before. Because as we all know, hidden variables have to be *very badly behaved indeed* in quantum mechanics (nonlocality, contextuality). Thus it would seem to be self-defeating for the informationist to take option 2.[6]

Turning then to the first answer. If the information the state represents is information about what the results of experiments will be, then the difficulty now is to say anything interesting that doesn't simply slide into instrumentalism. Instrumentalism, of course, is the general view that scientific theories do not seek to describe the laws governing unobservable things, but merely function as devices for predicting the outcomes of experiments. An instrumentalist view of the quantum state understands the state merely as a device for calculating the statistics of measurement outcomes. How is the current view any different, apart from having co-opted the vogue term 'information'?

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[6] A caveat. If one adopted an informational view of the state not in order to address the measurement problem; and not in order to relieve problems over nonlocality; if one could argue that it was *natural* for *quite other reasons*, perhaps, to take the state to represent information, then one might not be so moved by this objection; and one might willingly embrace the charge that one was dealing with hidden variables. Compare Spekkens (2007). Of course, one must then admit that it's not really the notion of information that is doing any of the interesting work.

If all that appeal to information were ultimately to amount to is a form of instrumentalism then we would not have achieved a particularly interesting—and certainly not a novel—interpretive doctrine. It would be an error to let a superficial re-packaging in fancy wrappings convince one that a product was worth buying after all. To the founding fathers of quantum mechanics, instrumentalism might conceivably have seemed a progressive epistemological doctrine, but that can scarcely be said to be the case now. As an option for interpreting quantum mechanics it arguably amounts more to a refusal to ask questions than to take quantum mechanics seriously.

3.1 The Problem of Factivity

But perhaps we have been a little too precipitate in our analysis. Might there be a subtlety of the informational approach that we have so far missed? Possibly. It is perhaps useful to highlight a subdivision in instrumentalist views that I have been glossing over.

Consider once more what might be called standard instrumentalism about the quantum state. This works as an interpretation of quantum mechanics (in so far as it works, that is) by witholding any descriptive claims at the level of individual systems. It restricts itself to making claims only about measurement results on ensembles of systems. (So on this view it would be a badly posed question to ask in quantum mechanics something like: how does an individual electron travel in a two-slit experiment? One can only ask about what observable *results* one might expect to see for *very many* electrons.)

So what if we were to insist that, by contrast with this, the distinctive job of information talk is to allow one to talk about *individual* systems, not just ensembles (look again at Hartle's wording above). Perhaps *this* is what would make the informational approach a worthwhile novel approach. Sadly, this approach faces a decisive objection.

Let us begin by noting that descriptions of the quantum state in terms of a person's knowledge or information will typically involve what might be called *mixed* ascriptions. That is, they will involve both the everyday semantic/epistemic concept of information and at the same time, the distinct technical concept of information introduced in information theory. We see this when we recognise that one will need to answer the question *what* information the state represents (Bell's question again); and will answer by talking of information *that* p or *about* q, both locutions signalling the everyday concept. At the same time, one might be interested in *how much* information the state represents, a phrase typically signalling the technical concept[7].

However, once we have the everyday concept of information in play, we need to recognise that the term 'information' is, just as the term 'knowledge' is, *factive.* That is, having the information that p entails that p is the case. Just as I can't know that p unless it is true that p, no more can I have the information that p unless p. And the difficulty that this presents for those wishing to understand the quantum state of an individual system as information is that this factivity entails just the sort of objectivity it was the original aim of the approach to avoid.

The standard instrumentalist does not face quite this problem. They avoided the problems associated with measurement and nonlocality by remaining at the level of statistics only. One doesn't describe individual systems at all and collapse will not be thought of as a real process, merely a change in what statistics one will expect. But for the proponent of the quantum state as information about individual systems, the essence of *their* approach, as we have seen above, is that different agents can assign different states to a given system because they have different information regarding it, but without disagreeing. In the Wigner's friend scenario, there would be no mysterious collapse, both agents simply ascribe a different state to the system being measured; and there is no one correct state which is an objective property of the system. Similarly with the EPR case.

But the factivity of information and knowledge put paid to these forms of argument: if the quantum state represents what one knows, or what information one has, then things have to be as they are known to be. If I know what the probability distribution for measurements on a system are, then they must objectively be thus-and-so. It is a matter of right or wrong determined by what the properties of the system are. Or

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[7] As noted above, consult Timpson (2004, 2008a,b) for more on the distinction between these concepts. It is plausible to suppose that at least part of the common failure to distinguish sufficiently between the everyday and technical concepts of information may be traced to the existence of mixed contexts in which the two distinct concepts are employed in the same breath; and confusingly, using the same word.

again, if Alice performs a measurement on her half of the entangled pair and therefore subsequently knows the pure state of Bob's system, then his system objectively has to be in that state. It is now a determinate matter of fact that some measurement at Bob's location will have a definite outcome whereas before it didn't. We are forced once more, like it or not, to talk about objective properties that systems possess; moreover, objective properties that can be changed at a distance.

So it seems that this approach runs aground. Adopting 'information' does not, after all free us from the objectivity that was causing the trouble in the first place. If there is to be any mileage, therefore, in approaches that analyse the quantum state in terms of cognitive states, one can't choose knowledge; and one must drop information. The state to choose would instead be *belief*, for believing that p does not entail p. For an approach that does just this, see the quantum Bayesianism of Caves, Fuchs and Shack (e.g. Fuchs (2002); Caves et al. (2006)).

4 If not instrumentalism, axiomatics instead?

Let us change tack. Steering between the horns of the dilemma of hidden variables versus instrumentalism proves difficult, maybe impossible. Perhaps we would do better to explore instead the possibility that the concept of information might have a role to play in rendering quantum mechanics more perspicuous via a suitable axiomatisation in information-theoretic terms. We shall focus on Zeilinger's version of this project as it links in interesting ways with our two overall themes.

Zeilinger (1999) suggests that we can render quantum mechanics more readily intelligible when we see how various of its fundamental and distinctive features can be derived from a simple principle:

> **Foundational Principle**:*An elementary system represents the truth value of one proposition.*

This is also expressed as the claim that elementary systems carry only one bit of information. The idea is that we have here something akin to the Principle of Relativity in special relativity, or to the Principle of Equivalence in general relativity; a simple and intuitively compelling principle which plays a key role in deriving the structure of the theory. In particular, Zeilinger argues that the principle allows us to understand both where the *irreducible* randomness of quantum mechanics and where entanglement come from. (Both, surely, centrally quantum—and centrally mysterious—features.) Elementary systems are components that are arrived at as the end point of a process of analysis. One begins by analysing a composite system into smaller component parts. Zeilinger then suggests that it is natural to assume that each consituent system will require fewer propositions for its description than the composite[8] and we might furthermore expect to reach a limit:

> ...the limit is reached when an individual system represents the truth value to one proposition only. Such a system we call an *elementary system.* (Zeilinger, 1999, p.635)

We might term the propositions in question *elementary propositions* too. Notice that the Foundational Principle is now revealed to be a tautology, or perhaps an analytic truth: a definition of 'elementary system'. One might be surprised that much could then follow from this on its own. This attitude proves warranted.

Zeilinger means something quite specific by 'proposition'. As in the quantum-logical tradition, it means something that represents an experimental question; and a truth-value assignment to a proposition corresponds to a yes/no answer to the experimental question. This allows us to formulate the principle more perspicuously as the claim:

> *The state of an elementary system specifies the answer to a single yes/no experimental question.*

One might not agree that this is a suitably unrestricted conception of the state of a system (compare the de Broglie-Bohm theory, for example, whose elements of holism and contextuality render this conception quite inapposite) but let us put this worry to one side and focus instead on what work the Foundational Principle is supposed to do

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[8] Is it? Only relative to a fixed system of concepts adequate to describe all levels of physical complexity; i.e., in which one begins with elementary propositions describing basic objects; and more complex objects are described by truth-functional combinations of these elementary propositions. (Consider: one could plausibly maintain that it takes fewer propositions to describe a *table* adequately than it does to describe an electron. Doesn't the sheer effort involved in science show that it typically gets *harder* to describe things the smaller they are?) Zeilinger's approach here bears marked similarities to Wittgenstein's views in the *Tractatus Logico-Philosophicus.*

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\begin{aligned}
|\phi^+\rangle &= 1/\sqrt{2}(|\uparrow\rangle|\uparrow\rangle + |\downarrow\rangle|\downarrow\rangle) \\
|\phi^-\rangle &= 1/\sqrt{2}(|\uparrow\rangle|\uparrow\rangle - |\downarrow\rangle|\downarrow\rangle) \\
|\psi^+\rangle &= 1/\sqrt{2}(|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle) \\
|\psi^-\rangle &= 1/\sqrt{2}(|\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle)
\end{aligned}
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Table 1: The four Bell states, a basis of maximally entangled two-party states.

within its own domain. The proposed explanation of the genesis of quantum randomness is very simple. Given the Foundational Principle,

> ...an elementary system cannot carry enough information to provide definite answers to all questions that could be asked experimentally (Zeilinger, 1999, p.636).

Those questions which don't receive a definite answer must then receive a random answer; and furthermore, that randomness *must* be irreducible, as if it *could* be reduced to hidden properties, then the system would really be carrying more than one bit of information, in violation of the principle (assuming that the system was in fact elementary).

For the explanation of entanglement: Suppose we have N systems and they have N bits of information associated with them. Entanglement results when all those bits of information are used up in specifying *joint* properties of the system, rather than individual properties, or more generally, when more information is in the joint properties than is possible classically (Brukner et al., 2001).

To illustrate the claim about entanglement we may use the case of two qubits. Consider the four maximally entangled bipartite quantum states known as the *Bell states* (Table 1). Each of these is a joint eigenstate of the observables $\sigma_x \otimes \sigma_x$ and $\sigma_y \otimes \sigma_y$. From the Foundational Principle, only two bits of information are associated with our two systems, i.e., the states of these systems can specify the answer to two experimental questions only. If the two questions whose answers are specified are 'Are both spins in the same direction along x?' ($1/2(\mathbf{1} \otimes \mathbf{1} + \sigma_x \otimes \sigma_x)$) and 'Are both spins in the same direction along y?' ($1/2(\mathbf{1} \otimes \mathbf{1} + \sigma_y \otimes \sigma_y)$), then we end up with a maximally entangled state. The answer "yes, yes" would give use the state $|\phi^+\rangle$; "yes, no", the state $|\psi^+\rangle$; "no, yes", the state $|\phi^-\rangle$; and "no, no", the singlet state $|\psi^-\rangle$.

By contrast, if the two questions had been ‘Are both spins in the same direction along x?’ and ‘Is the spin of particle 1 up along x?’, the information would not have all been used up specifying *joint* properties and we would have instead a product state, a joint eigenstate of $\sigma_x \otimes \sigma_x$ and $\sigma_x \otimes \mathbf{1}$. “Yes, yes” would give us the state $|\uparrow\rangle|\uparrow\rangle$; “yes, no” would give us $|\downarrow\rangle|\downarrow\rangle$; “no, yes” the state $|\uparrow\rangle|\downarrow\rangle$; and “no, no” the state $|\downarrow\rangle|\uparrow\rangle$. The way the information is distributed over the systems is crucial in determining whether we have an entangled or a non-entangled state.

At first glance, these explanations might appear to have something going for them, but only at first glance. Unfortunately they suffer from a deep flaw. No attention has been paid to the structure of the set of experimental questions on individual and joint systems, yet it is precisely this which is essential to the appearance of randomness and entanglement. The Foundational Principle places no constraints on the set of experimental questions at all, so it cannot do the job of explaining the existence of quantum randomness and entanglement[9].

Consider: irreducible randomness would only arise if there were more experimental questions to be asked of an elementary system than its most detailed state description would provide an answer for[10]. But what determines how many experimental questions there are and how they relate to one another? Certainly not the Foundational Principle. The principle doesn’t explain why it is that having given the finest grained description of the system that is possible, any space for randomness still remains. Why isn’t the one bit enough on its own, for example? In the quantum case, because the set of experimental questions is in one-to-one correlation with projectors onto a complex Hilbert space and the simplest non-trivial state space is two-dimensional. But that is the structure we are supposed to be deriving, it is not something we can help ourselves to. Why should the set of experimental questions be structured like *that*? Compare with the state-space of a classical Ising model spin: these objects only have two states: up or down; here the one bit we are allowed per system is quite sufficient to answer all experimental questions that could be asked. The Foundational Principle is clearly powerless to distinguish between

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[9] These objections were presented in Timpson (2003).

[10] Suppose, for simplicity, that we have some kind of independent access to the notion of an elementary system, so we can tell whether a system really is supposed to be elementary or not.

the two cases.

The case of entanglement is similar. If we return to the starting point and consider our N elementary systems, all that the Foundational Principle tells us regarding these systems is that their individual states specify the answer to a single yes/no question concerning each system individually. There is, as yet, no suggestion of how this relates to joint properties of the combined system. Some assumption needs to be made before we can go further. For instance, we need to enquire whether there are supposed to be experimental questions regarding the joint system which can be posed and answered that are not equivalent to questions and answers for the systems taken individually. (We know that this will be the case, given the structure of quantum mechanics, but again we are not allowed to *assume* this structure, if we are engaged in a foundational project.[11]) If this *is* the case then there can be a difference in the information associated with correlations (i.e., regarding answers to questions about joint properties) and the information regarding individual properties. But then we need to ask: why is it that there exist sets of experimental questions to which the assignment of truth values is not equivalent to an assignment of truth values to experimental questions regarding individual systems?

Because such sets of questions exist, more information can be 'in the correlations' than in individual properties. Stating that there is more information in correlations than in individual properties is then to report that such sets of non-equivalent questions exist, *but it does not explain why they do so.* However, it is surely this that demands explanation—why is it not simply the case that all truth value assignments to experimental questions are reducible to truth value assignments to experimental questions regarding individual properties, as they are in the classical case? That is, why does entanglement exist? In the absence of an answer to the question when posed in this manner, the suggested explanation following from the Foundational Principle seems dangerously close to the vacuous claim that entanglement results when the quantum state of the joint system is not a separable state.

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[11] To illustrate, a simultaneous truth value assignment for the experiments $\sigma_x \otimes \sigma_x$ and $\sigma_y \otimes \sigma_y$ cannot be reduced to one for experiments of the form $\mathbf{1} \otimes \mathbf{a}.\boldsymbol{\sigma}, \mathbf{b}.\boldsymbol{\sigma} \otimes \mathbf{1}$.

As it stands, the Foundational Principle is wholly unsuccessful. Might we be able to salvage something from the approach, however? Perhaps if we were to add further axioms that entailed something about the structure of the set of experimental questions, progress could be made. A possible addition might be a postulate Rovelli (1996) adopts: *It is always possible to acquire new information about a system.* One wouldn't be terribly impressed by an explanation of irreducible randomness invoking the Foundational Principle and this postulate, however, as it would look rather too much like putting the answer in by hand. But there might be other virtues of the system to be explored.

This consideration raises a final point. Evidently more axioms need to be added if we are to derive any useful work from the Foundational Principle. But recall that to provide a perspicuous information-theoretic axiomatisation, we will need intuitively compelling axioms (or at least *some* of them) which also play a substantial role. It would not do simply to add any old axioms that would have the effect of recovering the correct structure of experimental questions, otherwise there is no explanatory gain to be had. Recall that there has been considerable progress in the quantum logical tradition of providing axiomatisations of quantum mechanics (see, e.g., Aerts and Aerts (2005) for a succinct review), but it is not clear that *these* approaches render quantum mechanics any less mysterious or any more intuitively understandable. It is not clear, in any case, that this is really their purpose.

5 Why the Quantum?

We have seen that there are formal difficulties with Zeilinger's approach; let us now consider some of its more philosophical underpinnings. There are clear affinities between the views Zeilinger expresses and Wheeler's It from Bit proposal. For example, Zeilinger states that, as he intends it,

> that a system "represents" the truth value of a proposition...only implies what can be said about possible measurement results. (Zeilinger, 1999, p.635)

Moreover, on his view, the results of measurement do not pertain to an externally existing mind-independent world; rather his view is an immaterialist one: properties are assigned to objects only on the basis of observation and are held only as long as they do not contradict further observation; and 'In fact, the object therefore is a useful construct connecting observations' (Zeilinger, 1999, p.633)[12]. Extreme subjectivism is kept in check by the requirement that there be intersubjective agreement between different agent's 'mentally constructed objects' (Zeilinger, 1999, p.634). Clearly, this kind of immaterialist setting would make the Foundational Principle more plausibly appear a good starting point for theorising.

So Zeilinger and Wheeler seem to share an immaterialist metaphysics. Of particular interest, however, is a striking passage in which Zeilinger suggests that his Foundational Principle might provide an answer to Wheeler's question 'Why the quantum?' in a way that chimes with the Bohrian thought that the structure of quantum theory is a consequence of limitations on what can be said about the world:

> The most fundamental viewpoint here is that the quantum is a consequence of what can be said about the world. Since what can be said has to be expressed in propositions and since the most elementary statement is a single proposition, quantization follows if the most elementary system represents just a single proposition. (Zeilinger, 1999, p.642)

Of course, we have already, in effect, seen that there is a crucial non-sequitur here. Quantization only follows if the propositions are projection operators on a complex Hilbert space. Why the world has to be described *that* way is the question that would really need to be answered in answering Wheeler's question; and the Foundational Principle does not help us. But it is interesting to delve a little further into why this non-sequitur is present. Reflect on the similarity between Zeilinger's statement and that famously attributed to Bohr by Petersen:

> There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature *is*. Physics concerns what we can say about nature. (Petersen, 1963, p.12)

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[12] It is perhaps unnecessary to add that if the forgoing is supposed to be an argument for the immaterialist position, it is an extremely weak one, failing as it does, for example, to distinguish between the grounds on which one might assert a proposition and what would thereby have been asserted.

The last sentence is particularly pertinent: 'Physics concerns what we can say about nature.' Compare again, another statement of Zeilinger's, '...what can be said about Nature has a constitutive contribution on what can be "real".' (Reported in Fuchs (2003, p.615)).

I think we find in these sentiments a crucial strand contributing to the thought that the rise of quantum information theory supports an informational immaterialism. If quantum mechanics reveals that the true subject matter of physics is what can be said, rather than how things are, then this seems very close to saying that what is fundamental is the play of information across our psyches. The development of a quantum theory of information merely exacerbates this thought stemming from the Copenhagen tradition.

However, it is important to recognise that there is a very obvious difficulty with the thought that what can be said provides a consitutive contribution to what can be real and that physics correspondingly concerns what we can say about nature. Simply reflect that some explanation needs to be given of where the relevant constraints on what can be said come from. Surely there could be no other source for these constraints than the way the world actually is—it can't *merely* be a matter of language[13]. It is because of the unbending nature of the world that we find the need to move, for example, from classical to quantum physics; that we find the need to revise our theories in the face of recalcitrant experience. Zeilinger and Bohr (in the quotation above) would thus seem to be putting the cart before the horse, to at least some degree. Schematically, it's the way the world is (independently of our attempted description or systematisation of it) that determines what can usefully be said about it, and that ultimately determines what sets of concepts will prove most appropriate in our scientific theorising. It is failure to recognise this simple truth that accounts, I suggest, for the otherwise glaring non-sequitur in the proposed answer to 'Why the quantum?'. One can't expect a substantive

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[13] Of course, what statements can be made depends on what concepts we possess; and, trivially, in order to succeed in making a statement, one needs to obey the appropriate linguistic rules. But the point at issue is what can make one set of concepts more fit for our scientific theorising than another? For example, why do we have to replace commuting classical physical quantities with non-commuting quantum observables? As Quine perspicuously notes '...truth in general depends on both language and extra-linguistic fact. The statement "Brutus killed Caesar" would be false if the world had been different in certain ways, but it would also be false if the word "killed" happened to have the sense of "begat".'(Quine, 1953, p.36). The world is required to provide the extra-linguistic component that will make one set of concepts more useful than another; furthermore, without an extra-lingustic component to truth, we could only ever have analytic truths—and that would no longer be physics.

empirical truth (e.g., about the correct structure of the set of experimental questions) to follow from a simple definitional statement like the Foundational Principle.

Another point can be drawn from the Petersen quotation. With its focus on the level of physical *description* and what can be *said* about nature (as opposed to how nature is) this passage can be seen to provide us with an example of what is often known as *semantic ascent*.

Semantic ascent is the move from what Carnap called the material mode to the formal mode, that is, roughly speaking, from talking about things to talking about words. As Quine says, '*semantic ascent*...is the shift from talking in certain terms to talking about them' (Quine, 1960, p.271). Bohr, it would seem, would have us ascend from the level of using words within our theory, to the level of describing our descriptions. This, the suggestion is, is the true task of physics.

But does such semantic ascent really achieve very much here? Far from it. It is true, but entirely trivial, that our subject matter will not be the world if we semantically ascend. It would be just as true in classical mechanics, say, as in quantum mechanics. There is indeed a sense in which there would be no quantum world at the level of our interest, but only because we are talking about words rather than the world; talking *about* various terms rather than *in* them.

Crucially, the fact that one has ascended doesn't make the level one has ascended from go away: notice that one can always force descent by asking 'So, what was said?'. It might perhaps be felt that here lies the real import of the Bohr quote and what serves to distinguish the quantum from the classical case. In the quantum case, we might be supposed to imagine that one *can* intelligibly kick away the lower level, having made the semantic ascent. But such a suggestion ('vertiginous semantic ascent', as it might be called) is in fact incoherent. It would amount to the claim that the 'descent' question 'So: what was said?' becomes unintelligible, but this would entail that the terms under discussion have to become entirely devoid of meaning, and as such they would have no role whatsoever in physics.

The upshot is that we can't shirk any of the problems of interpreting quantum mechanics by indulging in semantic ascent. It doesn't remove us from the fray nor amount to an interpretation of quantum mechanics in itself. The world doesn't disappear because we may be talking about the terms in which we describe it. The interpretational questions that have always plagued quantum theory concern what stance should be taken to claims made *using* the terms within a theory; and all the usual options (realism, instrumentalism and hybrids thereof) will remain open irrespective of ascent.

If this reading I have suggested is indeed the most intelligible reading of the Bohr quotation then it becomes clear that 'there is no quantum world' and 'physics concerns what we can say about nature' are not after all immaterialist mantras. Rather they are truistic consequences of an innocuous semantic ascent. In fact its hard to see how they could be anything else while retaining the least hint of plausibility.

6 Conclusion

My aim in this essay has been to clear the ground a little. Quantum information theory is indeed a rich and intriguing subject for philosophical study, but if we are to be live to what new consequences it may have for our understanding of quantum mechanics in particular and physics in general, then we do better if we are able to separate new from old; and if we turn a suitably sceptical eye towards the claims of our familiar pair instrumentalism and immaterialism.

Elsewhere I have distinguished direct from indirect approaches to securing a philosophical dividend from quantum information theory. Among the direct approaches we can count taking the quantum state to be information and taking quantum information to support informational immaterialism. More interesting and plausible than these proposals, I suggest, are the indirect approaches. Amongst these are attempts such as Zeilinger's to learn something useful about the structure or axiomatics of quantum theory by reflecting on quantum information-theoretic phenomena; approaches that might look to quantum information theory to provide new analytic tools for investigating that structure; and approaches that look to suggested constraints on the power of computers, including quantum computers, as potential constraints on new physical laws. Whilst Zeilinger's particular programme suffers from the rather severe problems we have seen and is tangled up with instrumentalist and immaterialist threads of broadly Copenhagen origin, in general, the indirect approaches look by far the most promising potential sources of new insights stemming from quantum information theory. By contrast the two direct approaches that we have been considering are not in good shape. The informational approach to the quantum state seems unable to survive the hidden variables/instrumentalism dilemma; and the thought that quantum information theory does lend support to a form of immaterialism really seems to have very little to commend it.

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