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Quantum reaxiomatisations and information-theoretic interpretations of quantum theory

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ABSTRACT

Jeff Bub has developed an information-theoretic interpretation of quantum mechanics on the basis of the programme to reaxiomatise the theory in terms of information-theoretic principles. According to the most recent version of the interpretation, reaxiomatisation can dissolve some of the demands for explanation traditionally associated with the task of providing an interpretation for the theory. The key idea is that the real lesson we should take away from quantum mechanics is that the ‘structure of information’ is not what we thought it was. In particular a feature of the new structure is intrinsic randomness of measurement, which allegedly dissolves a significant part of the measurement problem. I argue that it is difficult to find an appropriate argument to support the claim that measurement is intrinsically random in the relevant sense.

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1. Introduction

Over the last 25 or so years, classical information theory has been fruitfully combined with quantum theory to produce the exploding new field of quantum information theory (Nielsen and Chuang (2000)). After a heady decade in the 1990s where new insights into quantum phenomena were combined with the development of new technologies like quantum computation and quantum cryptography, there began to be suggestions that quantum information theory might provide the resources to tackle the foundations of the theory in a new way. In particular, a research programme gradually developed of trying to reaxiomatise the theory in terms of broadly information-theoretic principles. That this programme might have implications for the traditional conceptual problems and for the interpretation of quantum theory is an idea which has been developed in stages by Jeff Bub, who has argued for what he calls an ‘information-theoretic interpretation’ of quantum theory (Bub (2000); Clifton, Bub, and Halvorson (2003); Bub (2004, 2005); Bub and Pitowsky (2010); Bub (2011, 2014, 2015)). Throughout this work, Bub has been guided by an analogy with Einstein’s use of postulates in special relativity. Different ways of deploying this analogy have resulted in several different lines of argument, some of which have already been critiqued in the literature. I summarise these discussions before addressing the most

recent line of argument. The main idea of this argument is that reaxiomatisations can dissolve some of the demands for explanation traditionally associated with the task of providing an interpretation for the theory. Although this general notion has some plausibility, I will argue that the quantum reconstructions have not provided the kind of specific argument that would make it work in a similar way to special relativity. Nonetheless, the information-theoretic interpretation represents a welcome attempt to connect the interpretational project in quantum theory to ongoing developments in foundations.

2. The reaxiomatisation programme in quantum mechanics

The traditional formulation of quantum theory is based on axioms that associate states with vectors in complex Hilbert spaces, observables with Hermitian operators and which include the ‘Born rule’ for calculating the probabilities of measurement outcomes. The theory works very well empirically, but there is still a deep puzzle about why these axioms are true, and many physicists have been dissatisfied with them. Hardy, for example, describes the standard axioms as ‘rather obscure’ (Hardy (2001)). Mueller and Masanes say they ‘seem arbitrary and do not have a clear meaning’ (Mueller and Masanes (2013)). Dissatisfaction with the standard formulations of the theory have fuelled a programme which aims to reaxiomatise the theory in terms of postulates which are clearer, more ‘reasonable’ and more physically motivated. These efforts typically take a general framework for expressing a broad class of

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possible theories and attempt to discover the principles that uniquely locate quantum theory within that framework.

Part of the programme grew out of the analysis of nonlocality. Quantum correlations violate Bell inequalities, yet quantum measurement does not allow signalling faster than light.¹ In 1994, Popescu and Rohrlich asked whether quantum theory is the only theory exhibiting nonlocality (in the sense of Bell inequality violation) and no-signalling (Popescu and Rohrlich (1994)). They showed that there can in fact be a whole family of theories which respect no-signalling and violate Bell inequalities. The correlations allowed by some of these theories are super-non-local in that they violate the Bell inequalities to a greater extent than quantum correlations. The general set of correlations which do not allow signalling comprise a polytope. Quantum correlations form a convex set within that no-signalling polytope. Within the quantum convex set, there is a local polytope of purely classical correlations. The work of Popescu and Rohrlich stimulated the search for some simple principle or principles that would characterise the boundary of the quantum convex set (Allcock, Brunner, Pawłowski, and Scarani (2009); de la Torre, Masanes, Short, and Mueller (2012); Navascués, Guryanova, Hoban, and Acín (2015)).

A number of people have also thought that in some aspects quantum theory looks like a modified form of probability theory. This idea has been explored in the framework of ‘generalised probability theories’, which defines the operational basis for any physical theory of a statistical nature (Mackey (1963); Ludwig (1985); Janotta and Hinrichsen (2014)). The primitives in this framework are preparation devices, transformation devices and measurement devices. Mathematical objects are associated with each of these – which are operational states, transformations and effects of measurements. A particular theory is characterised by the set of operational states S that it associates with preparations, and the set of mathematically described ‘operational effects’ R associated with measurements.

In 2001, Lucien Hardy imposed a small set of ‘reasonable axioms’ on this type of framework, and succeeded in showing that they picked out quantum theory uniquely. Since then, Hardy and other authors have done a great deal of refinement to the axioms system, resulting in a number of variants in a similar vein (Hardy (2002); Mueller and Masanes (2013); Hardy (2013); Dakic and Brukner (2011); Chiribella, D’Ariano, and Perinotti (2011); Chiribella and Spekkens (2016)).

In 2003, philosophers of physics produced a reaxiomatisation of quantum theory in the framework of C^* -algebras. This framework was also taken to be a general framework which would allow a number of possible theories to be expressed. Clifton, Bub and Halvorson imposed three fundamental information-theoretic constraints on this framework, and proved the ‘CBH theorem’, showing that these ‘suffice to entail that the observables and state space of a physical theory are quantum-mechanical’ (Clifton et al. (2003)). It later emerged that the C^* -algebra framework was fairly restrictive, and so the result was perhaps not as compelling as it first appeared (Halvorson (2004)). Nonetheless, because this is the reconstruction effort with which philosophers have been most familiar, most discussions of the implications of reaxiomatisations for interpretation of the theory have focused on the CBH result. However, in

principle much of the discussion can be generalised to the other reconstruction efforts in the foundations of quantum theory.

One of the key motivations for reaxiomatising an existing theory, such as quantum mechanics, is to make progress in developing new theories. Many of those working in the reaxiomatisation programme think that quantum theory is not a final theory, particularly in light of problems concerning how to combine it with the theory of general relativity. The general strategy of trying to understand where the theory comes from in a general operational framework is thought to be a useful way to discover the form of quantum theory’s successor (Hardy (2007)).

The reaxiomatisation effort is clearly also directed at deepening our understanding of quantum theory, and in this sense it should have relevance for how the theory is interpreted. However, for many at this stage, this is mostly a promissory note – the idea appears to be that once progress in this direction is made, the right interpretation will suggest itself. By contrast, Bub argues that the reaxiomatisation efforts already offer insights that delineate a new interpretation, which he calls the ‘information-theoretic interpretation’.

3. The information-theoretic interpretation

The information-theoretic interpretation of quantum theory has been developed in large part by drawing an analogy with Einstein’s use of postulates in the theory of special relativity. Einstein based his theory on two postulates, the Principle of Relativity and the Light Postulate, which he took to be securely founded in experience. These two postulates appear at first sight incompatible, but Einstein showed that they can be made compatible by revising the concept of time. The key insight is that judgments of simultaneity may depend on the inertial frame. Two events may be simultaneous in one frame, yet not in another. The recognition of the relativity of simultaneity paved the way for the development of a new space-time concept, which was later formalised as Minkowski space-time.

Einstein’s use of postulates has been held up as an exemplar by physicists working in the quantum reaxiomatisation programme. Early on, there was a rallying cry from Chris Fuchs for developing new axioms for quantum theory of an information-theoretic character, and he invoked the special relativity example (Fuchs (2002), p. 4). Fuchs called for a concerted effort in the quantum community to try to produce principles which would achieve for quantum mechanics what Einstein had achieved for special relativity, and argued that the new field of quantum information might provide tools for doing this.

Bub motivates his view by the idea that Einstein’s derivation of special relativity from principles did contribute in an essential way to interpretation of the theory. The claim then is that it is possible that reaxiomatisations or reconstructions of quantum theory could make a similar contribution to the interpretation of quantum theory. Throughout his work, Bub has attempted to extract the core of what was going on in the special relativity case, and to set it in a general context, so that it might also be seen to apply to quantum mechanics. I suggest that we can distinguish three different lines of argument which all share this same general approach. The first two have already been extensively criticised in the literature. I will summarise these in the next two sections (3.1 and 3.2), before turning to my main task of outlining and analysing the third and most recent line of argument in section 3.3.

3.1. Principle theory as interpretation

The first line of argument is found in Clifton et al. (2003), and it makes use of Einstein’s own distinction between ‘principle’ and ‘constructive’ theories. Einstein distinguished between two ways

¹ Suppose we have two space-like separated observers Alice and Bob. The no-signalling principle says that when Alice and Bob perform local measurements, Alice’s measurements can have no influence on the statistics for the outcomes of Bob’s measurements (and vice versa). This constraint can be written as $p(A|a, b) = p(A|a)$ and $p(B|a, b) = p(B|b)$, where A and B are the outcomes of local measurements and a and b are Alice and Bob’s measurement apparatus settings.

that a scientific theory might be built up. On the one hand, a theory might be ‘constructive’: it then postulates hypothetical elements out of which complex phenomena are to be built up. For example ‘the kinetic theory of gases seeks to reduce mechanical, thermal and diffusional processes to movements of molecules’ (Einstein (1919), p. 228) Einstein contrasted constructive theories with ‘principle theories’. Principle theories are based not on a framework of hypothetical entities, but on empirically secure postulates or principles:

The elements which form their basis and starting point are not hypothetically constructed but empirically discovered ones, general characteristics of natural processes, principles that give rise to mathematically formulated criteria which the separate processes or the theoretical representations of them have to satisfy. (Einstein (1919), p. 228).

Einstein said that in creating special relativity, he had explicitly tried to construct a principle theory. That contrasted with the work of predecessors like Lorentz, who had been attempting to constructively build up a theory of electrodynamics from what was understood of the molecular physics. Einstein turned to a principle theory approach because he thought that the state of molecular understanding was insufficiently good at the time to attempt a more constructive theory.

Clifton, Bub and Halvorson suggested that their reconstruction of quantum theory from information-theoretic principles allows quantum mechanics to be interpreted as a principle theory:

The foundational significance of our derivation, as we see it, is that quantum mechanics should be interpreted as a *principle theory*, where the principles at issue are information-theoretic (Clifton et al. (2003), p. 1588).

They then claimed that a derivation from principles can be thought of as itself an interpretation for the theory:

Einstein’s derivation provides an interpretation for relativity theory: a description of the conditions under which the theory would be true, in terms of certain principles that constrain the law-like behavior of physical systems. It is in this sense that our derivation of quantum theory from information-theoretic principles can be understood as an interpretation of quantum theory: the theory can now be seen as reflecting the constraints imposed on the theoretical representations of physical processes by these principles. (Clifton et al. (2003), pp. 1588–1589).

There is of course a disanalogy between special relativity and quantum theory in terms of their origins. Because of Einstein’s derivation from postulates, it was from the outset understood that the theory had the structure it did ‘as a consequence of the fact that we live in a world in which natural processes are subject to certain constraints’ (Clifton et al. (2003), p. 1588). By contrast, quantum theory ‘was born as a recipe or algorithm for calculating the expectation values of observables measured by macroscopic measuring instruments’ (Clifton et al. (2003), p. 1588). Clifton et al. try to bring out the significance of Einstein’s derivation by asking us to imagine a world where ‘the special theory of relativity was first formulated geometrically by Minkowski rather than Einstein, as an algorithm for relativistic kinematics and the Lorentz transformation, which is incompatible with the kinematics of Newtonian space-time’ (Clifton et al. (2003), p. 1588). The point is that

from the outset quantum theory lacked the deeper explanation of its structure that Einstein’s derivation had provided for the new space-time structure in special relativity.

In summary, the Clifton-Bub-Halvorson argument goes as follows:

1. Einstein’s derivation from the Principle of Relativity and the Light Postulate established special relativity as a principle theory.
2. The CBH derivation of quantum theory from information theoretic principles also establishes quantum mechanics as a principle theory.
3. A principle theory can serve as an interpretation for a theory.

Therefore, the CBH reconstruction can serve as an interpretation for quantum theory.

The argument could also be generalised to any quantum reconstruction from principles which could be argued to establish quantum mechanics as a principle theory. The main criticism of the argument has been directed at premise 3. Usually the interpretation of a theory is taken to be an account of what the world that the theory describes must be like: it concerns the ontology behind the theory. Clifton, Bub and Halvorson, on the other hand, talk about an interpretation as a kind of explanation of why the theory takes the particular form it does. Although this is clearly an important question, it is not the same as asking for an account of what the world that the theory deals with is like. A number of authors have therefore resisted the idea that the CBH reconstruction could, even in principle, provide an interpretation in the traditional sense, at least not a realist interpretation (Duwell (2007), Hagar and Hemmo (2006), Feline (2016)). The thought has often been that a full interpretation of a theory is either akin to or requires a constructive theory, and the formulation of a principle theory does not preclude the formulation of a constructive theory.

Brown and Timpson argue that even in the case of special relativity, Einstein’s postulates did not provide an interpretation (Brown and Timpson (2006)). Rather, they suggest, the development of special relativity as a principle theory was an expedient that Einstein had to take, given the state of physics around the turn of the century, and Einstein himself still saw the theory as in need of completion by a more constructive account. The principle theory of special relativity was developed in an operational framework, treating rods and clocks as primitive unstructured entities, but Einstein continued to see the need to provide a constructive theory of the workings of these elements. In general, if a principle theory is formulated in an operational framework, it contains some ‘black boxes’, and until those are filled in, neither a full constructive theory nor a complete interpretation are provided. Also in Einstein’s other paradigm example of a principle theory, namely thermodynamics, the explanatory structures derived from the thermodynamic postulates do not replace the constructive, statistical mechanical explanation of the phenomena. Rather statistical mechanics is expected to account for the explanatory structures in thermodynamics, such as the entropy principle. Thus, Brown and Timpson argue that ‘it is far from clear that (Einstein) would have encouraged the use of his SR – his 1905 SR – as a template for an “interpretation” of quantum theory. Or rather, for a *fundamental* interpretation’ (Brown and Timpson (2006), p. 12).

3.2. In principle underdetermination

In Bub (2004, 2005), Bub also produces a second line of argument, which does not rely on the claim that the principle theory itself constitutes an interpretation of the theory. Rather he takes it that the derivation of the theory from information theoretic

principles rules out a class of possible interpretations of the theory by a kind of underdetermination argument. The key idea is that theories which extend quantum mechanics by incorporating hidden variables so as to give a mechanical account of measurement interactions are shown by a reconstruction like CBH to have no 'excess empirical content' over quantum theory *in principle* Bub (2005), p. 555. This message is reinforced again by the comparison with special relativity:

insofar as a constructive theory like Lorentz's theory is constrained by the requirement to reproduce the empirical content of the principles of special relativity (which means that the aether as a rest frame for electromagnetic phenomena must, in principle, be undetectable), such a theory can have no excess empirical content over special relativity. (Bub (2005), p. 555).

Similarly, he argues

if the information-theoretic constraints are satisfied, a constructive theory like Bohm's theory can have no excess empirical content over a quantum theory. Just as in the case of Lorentz's theory, Bohm's theory will have to posit contingent assumptions to hide the additional mechanical structures (the hidden variables will have to remain hidden), so that *in principle*, as a matter of physical law, there *could not be* any evidence favouring the theory over quantum theory. (Bub (2005), p. 555).

He then argues that this in principle underdetermination means that 'no mechanical theory of quantum phenomena that includes an account of measurement interactions can be acceptable' (Bub (2004), p. 241).

This argument has been criticised as question-begging (Timpson (2013), Duwell (2007)). The idea is that it is only if the information-theoretic constraints are regarded as holding 'as a matter of physical law' that a theory like Bohm's will be seen as in principle empirically equivalent to quantum theory itself. However, a Bohmian might well deny that those constraints do have that status (See Timpson (2013) and Duwell (2007) for more in-depth critiques of this line of argument).

3.3. Explanatory displacement

In more recent expositions of the information-theoretic interpretation, a third line of argument is to be found (Bub and Pitowsky (2010); Bub (2011, 2014, 2015)). The claim is now very explicitly that an information-theoretic interpretation of quantum theory can dissolve the measurement problem, by showing that the problem is, in large part, a 'pseudo-problem'.

The argument is again based on the analogy with the case of special relativity, but now the idea is that what is distinctive in that case is that various phenomena, such as length contraction, can be explained kinematically with the aid of the new space-time structure, and that this removes the need to give a dynamical explanation such as was sought by Lorentz. There is therefore what I will call a kind of 'explanatory displacement': the kinematic explanation in terms of the new structure displaces the dynamical explanation, and this happens because the new structure has a certain features which make it apparent that the phenomenon required no further explanation beyond what is given by the kinematics.

Bub suggests that an analogous explanatory displacement occurs in quantum theory. As he sees it, quantum theory brings a new information-theoretic structure, which can be regarded as parallel to the Minkowski space-time in special relativity:

what is fundamental in the transition from classical to quantum physics is the recognition that *information in the physical sense has new structural features*, just as the transition from classical to relativistic physics rests on the recognition that space-time is structurally different from what we thought. (Bub (2011), p. 1).

The thought is then that just as the kinematic explanation of length contraction renders a dynamical explanation unnecessary, so the new quantum information structure can provide kinematic explanation of the measurement process which render a dynamical account unnecessary.

This leads, according to Bub, to a substantial dissolution of the measurement problem in quantum mechanics. The measurement problem concerns how to provide a dynamical account of the quantum measurement process which explains how definite measurement outcomes are achieved. Evolving the state of a microscopic quantum system and the state of a macroscopic measuring device using the Schroedinger equation results in an entangled state of the system and measuring apparatus. Bub distinguishes between a 'big' and a 'small' problem of measurement. The small measurement problem is to show how a classical ignorance-based probability distribution over the possible outcomes can arise when a measurement is performed ('explaining the dynamical emergence of an effectively classical probability space of macroscopic measurement outcomes in a quantum measurement process' (Bub and Pitowsky (2010), p. 438). The 'big' measurement problem, on the other hand, is to explain how individual measurement outcomes come about dynamically: 'how the cat + quantum-system-that-triggers-the-device goes from an entangled state to one of its components, i.e. a product state in which the cat is definitely alive or definitely dead and the quantum system is in one of two possible states'.

The claim then is that the big measurement problem is not one which needs to be solved because the new quantum information structure provides a kinematic explanation of measurement outcomes which renders a dynamical explanation of evolution to particular measurement outcomes unnecessary. Bub further suggests that the small measurement problem can be solved by decoherence arguments which explain how an effectively classical probability distribution arises (Bub and Pitowsky (2010); Bub (2015, 2016)).

The overall idea here is that a new structure in the theory may provide an autonomous, kinematic part of the explanation of phenomena, making a dynamical explanation unnecessary. Another way to put this is to say that the new structure itself, without needing to be further analysed, serves as part of the full constructive theory. Bub says:

Minkowski space-time is the constructive theory corresponding to Einstein's principle theory formulation of special relativity: it is a component of the kinematic part of the constructive theory of the constitution of matter provided by relativistic quantum theory. (Bub and Pitowsky (2010), p. 446).

And again, by analogy, he says that we should 'interpret Hilbert space as a constructive theory of information-theoretic structure or probabilistic structure, part of the kinematics of a full constructive theory of the constitution of matter' (Bub and Pitowsky (2010), p. 448).

This kind of purported dissolution of the big measurement problem requires that the kinematic explanation in terms of the new information-theoretic structure has a kind of autonomy which makes a deeper constructive analysis of the structure itself unnecessary. What secures this kind of status? A possible answer,

which would provide some continuity with the earlier instantiations of the information theoretic interpretation, is that it is the derivation from principles which secures this status. Einstein's derivation from principles provides an understanding for why Minkowski space-time has the structure that it does. It was only because it was clearly understood what lay behind the new space-time concept, and exactly why it differed from the Newtonian space-time concept, that it became possible to see certain phenomena, such as length contraction, as explained by the new space-time structure itself. Without such an explanation of the origins and significance of the new structure, this would not be possible. To see what contribution the principle theory can make, consider again CBH's counterfactual world where 'the special theory of relativity was first formulated geometrically by Minkowski rather than Einstein, as an algorithm for relativistic kinematics and the Lorentz transformation, which is incompatible with the kinematics of Newtonian space-time' (Clifton et al. (2003), p. 1588). In this kind of counterfactual world where Minkowski space-time was discovered as an empirically adequate but otherwise unexplained new structure, it seems much more doubtful that the Minkowski space-time could take over explanatory work in its own right.

3.3.1. The role of intrinsic randomness

The information-theoretic interpretation takes seriously the possibility that the kind of insight provided by Einstein's principle theory derivation of special relativity could in principle be repeated if an analogous reconstruction of quantum theory from principles is possible. However, this still raises the question of whether existing reaxiomatisations or reconstructions of quantum theory actually do provide a sufficiently analogous explanation of the new structure. In the case of special relativity, Einstein's postulates were not simply used to derive the Minkowski space-time. Rather they provided an insight into exactly what metaphysical assumption in the previous theory needed to be given up. The apparent incompatibility between the two postulates was resolved by the recognition that it was critical to give up on the notion of absolute simultaneity implicit in previous theories of space and time.

In the quantum case, the idea behind the information-theoretic interpretation is that it is the 'intrinsic randomness' of measurement which is the key feature of the new information structure. Bub takes it to be a consequence of this that the big measurement problem can be dissolved. Because the selection of a particular measurement outcome is intrinsically random, no further account of how it is arrived at is required.

The random selection of a definite outcome in a quantum measurement process is a feature of the nonclassical structure of information in a quantum world, just as Lorentz contraction is a feature of the Minkowski structure of space-time in a relativistic world (Bub (2016), p. 223).

In a measurement process the system just makes a random transition into the component state (in accordance with the probabilities dictated by QM, but otherwise unconstrained).

The definite occurrence of a particular event is constrained by the kinematic probabilistic correlations represented by the subspace structure of Hilbert space, and only by these correlations — it is otherwise free. (Bub (2011), p. 23).

Bub argues that the big measurement problem can be dissolved because the transition into a particular state on measurement is only constrained by the kinematic structure of the quantum

correlations. Because of the 'intrinsic randomness', no dynamical account of the measurement transition is needed.

If the universe is genuinely indeterministic and measurement outcomes are intrinsically random because the observable measured is indefinite, then it isn't possible to provide a dynamical explanation of how a system produces a definite outcome is measured — that's what it means for the measurement outcome to be *intrinsically* random. The random selection of a definite outcome in a quantum measurement process is a feature of the nonclassical structure of information in a quantum world, just as Lorentz contraction is a feature of the Minkowski structure of space-time in a relativistic world (Bub (2016), p. 223).

Overall, then, the argument appears to be the following:

1. A dynamical description of the measurement interaction between the system and the measurement device can account for the origins of a probability distribution over the macroscopic measurement outcomes, where the probabilities can be interpreted in terms of ignorance (the small measurement problem is solvable).
2. The remaining ('big') problem of measurement is to explain dynamically how a measurement interaction can produce a definite outcome.
3. Intrinsic randomness is a key feature of the new structure of information in quantum mechanics.
4. If there is intrinsic randomness in measurement, there is no need to provide a dynamical explanation of how a measurement interaction can produce a definite outcome (i.e. no need to solve the big measurement problem of 2).

Therefore, there is no need to solve the big measurement problem.

Bub's argument for point 1) invokes decoherence arguments from Hepp (1972) and Landsman (2007). I will not attempt to assess the viability of this point here. The success of the rest of the argument clearly depends on what is meant by 'intrinsic randomness'. As is apparent from the above quotation, the notion is closely connected to, if not identical with, the notion of genuine indeterminism. To specify this further we need to provide a definition.

Definition. A measurement outcome X is *determined* by a set of factors $\{Y\}$ if the conditional probability of X given those factors, $p(X|\{Y\})$ is either zero or one. In this case, X can also be specified as functionally dependent on the factors $\{Y\}$.

Given this Definition, we may now define what it means for a measurement outcome to be 'intrinsically random':

Definition. A measurement outcome is *intrinsically random* if it is not determined by the preparation, measurement setting and all ontological variables in the system. That is: the probability of the measurement outcome, given all those factors, is not either zero or one.

Such an understanding of intrinsic randomness would make sense of Bub's premise 4 above, because then it would not be possible to give any more fine-grained dynamical account of a particular measurement outcome since the outcome is not determined, even when all ontological variables are taken into account.²

² Timpson (2010) has attempted to argue against premise 4 by claiming that dynamics for a value state would still be needed. But if intrinsic randomness is understood as above, then such a dynamics for the evolution to particular individual outcomes would not be possible, since the value state is already part of the hidden variables.

The key question is now: is premise 3 of the above argument true? That is, can we really establish that intrinsic randomness is a feature of the quantum information-theoretic structure?

3.3.2. An argument for intrinsic randomness?

At first sight the idea that there might be an argument from principles for intrinsic randomness appears to have some plausibility. There have even been attempts in the quantum context to explicitly mimic Einstein's breakthrough. In 1994, Popescu and Rohrlich, citing Aharonov as a source, suggested an argument for indeterminism which closely mirrors the structure of Einstein's derivation of special relativity from postulates. They took non-locality, in the sense of violation of Bell's inequalities, as one axiom of the theory. A second postulate was relativistic causality, which they gloss as the impossibility of transmitting signals faster than light. The motivation for placing these two principles as axioms for the theory, is, as in the case of Einstein's derivation, that they are clearly operationally defined and empirically supported basic principles. The argument then parallels Einstein's:

The special theory of relativity can be deduced in its entirety from two axioms: the equivalence of inertial reference frames, and the constancy of the speed of light. Aharonov has proposed such a logical structure for quantum theory. Let us take, as axioms of quantum theory, relativistic causality and nonlocality. As an initial, immediate result, we deduce that quantum theory is not deterministic, otherwise these two axioms would be incompatible (Popescu and Rohrlich (1994), p. 2).

Thus the argument is the following:

1. Non-locality
2. Relativistic causality (No-signalling).

Therefore, indeterminism.

The idea seems to be something like the following: if you have entangled systems, but yet you can't use the entanglement to signal, this must be because there is actually no deterministic connection which can be exploited in order to signal.

This argument was presented more mathematically in Masanes et al. (2006), where it is presented as a demonstration that any nonlocal correlations which satisfy signal locality must be 'indeterministic'. According to Masanes et al. the upshot is that 'there are two kinds of randomness in any nonsignaling theory with nonlocal correlations. The first one reflects our ignorance and corresponds to those probability distributions that can be written as the convex combination of extreme points. But, like in QM, there is also an intrinsic randomness even for extreme points, or pure states' (Masanes et al. (2006), p. 7).

It looks then as though there is an argument for indeterminism which parallels Einstein's derivation in special relativity, and which could play a similar role in supporting claims that certain phenomena are explained by the new theoretical structure itself (the new structure of information), rather than requiring any constructive dynamical explanation. However, it is important to understand correctly the significance of the Popescu-Rohrlich-Masanes argument, a point which has been highlighted by Cavalcanti and Wiseman (2012). Cavalcanti and Wiseman show that the argument is not in fact an argument for indeterminism per se, but rather for a related operational notion of 'unpredictability'. In the literature, they point out, the presentation has been rather careless, and these two notions have not always been clearly distinguished. Denote the measurement settings of observers Alice

and Bob by a and b , and their measurement outcomes which we denote A and B . A model is 'deterministic' if

$$p(A, B|a, b, \kappa, \lambda) \in \{0, 1\}$$

which means that the measurement outcomes for Alice and Bob are a function of the values of the measurement settings, preparation and hidden variable. It satisfies 'predictability' if

$$p(A, B|a, b, \kappa) \in \{0, 1\}$$

which means that the measurement outcomes for Alice and Bob are a function of the values of the measurement settings and preparation alone. Unpredictability is an operational concept which doesn't rule out the possibility of determinism, when hidden variables are taken into account. As Cavalcanti and Wiseman point out: 'predictability implies determinism, but the converse is not true' (Cavalcanti and Wiseman (2012), p. 6). The significance of the Popescu-Rohrlich-Masanes result is not that we can draw the conclusion from nonlocality and signal locality that the theory is indeterministic, but rather that it is unpredictable. It should in fact be evident that the conclusion of the argument cannot be indeterminism, since we have a deterministic theory reproducing the quantum predictions, which is nonlocal and satisfies signal locality, in the form of Bohm's theory.

3.3.3. An indirect argument for intrinsic randomness?

Nonetheless, one might still think that something has been gained by establishing unpredictability on the basis of the postulates of non-locality (violation of Bell inequalities) and signal locality, which are arguably two empirically well-founded principles. This is where the analogy with the special relativity case comes back in. Bub argues that although we don't have a knock-down argument against Bohm's theory, nonetheless there is something wrong with continued efforts to construct deterministic interpretations for quantum mechanics. He compares this to attempts to keep on giving Lorentzian explanations using classical space-time, when a much simpler explanation is possible using Minkowski space-time. Lorentz's theory could provide a dynamical explanation for the phenomena that Einstein's theory explained kinematically, but it only worked for carefully chosen values of drag to cancel the ether wind. Similarly, once unpredictability is securely established for quantum mechanics, the only way a deterministic hidden variables theory will work is if the parameter values are set so as to still preclude signalling faster than light. Compared to Einstein's theory, a Lorentzian theory has the disadvantage of requiring fine-tuned parameter values. And in a similar fashion, one might think a deterministic hidden variables theory for quantum mechanics would also require too much fine-tuning.³

A recent theorem by Wood and Spekkens apparently provides a way to formalise this argument more precisely, but again, unfortunately the conclusion will not be indeterminism or intrinsic randomness of measurement. Wood and Spekkens investigate the problem of providing a causal explanation for quantum correlations, where a causal explanation is taken to be a causal graph model which gives rise to the observed probabilistic

³ It is possible to argue that one of the key elements of Inference to the Best Explanation is avoiding fine-tuning see Henderson (2013). From this point of view, Einstein's theory provided a better explanation than Lorentz's in part because it was less fine-tuned. Then the claim would be that even though we don't have an argument from principles to indeterminism, perhaps we can still argue by an inference to the best explanation: indeterminism provides the best explanation of unpredictability.

independences and conditional independences. They prove the following theorem:

$CAUSAL + NOFINE + QCORR \Rightarrow \text{contradiction}$ (Wood and Spekkens (2015), p. 24–5).

Here $QCORR$ is the conjunction of what we have called Non-locality, (namely the existence of entangled quantum states which violate a Bell inequality) No-signalling, (expressed by the conditional independences $A \perp b|a$ and $B \perp a|b$) and an assumption IND that the measurement settings are independently chosen by Alice and Bob, $a \perp b$.

$CAUSAL$ is the assumption that a probability distribution over the observed variables can be explained causally using the standard framework of causal models. In this formalism, a causal model consists of a causal structure and a set of causal parameters. The causal structure is a set of variables V and a set E of ordered pairs of V , where $\langle X, Y \rangle$ is in E if X is a direct cause of Y relative to V . A causal structure can be represented by a directed acyclic graph (DAG). Every variable in V is represented by a vertex in the graph, and every ordered pair $\langle X, Y \rangle$ in E is represented by a directed edge or arrow from X to Y . As well as the graph structure, the causal model also specifies a set of causal parameters, which give the conditional probability for every variable, given its parents $p(X|Parent(X))$. For variables with no parents (so-called 'exogenous' variables), the parameter is just a probability distribution over the variable itself. $CAUSAL$ assumes the Causal Markov Condition, which generalises Reichenbach's principle of the common cause, and tells us what conditional independences in the probabilistic correlations are to be associated with a causal graph of a particular structure.⁴

$NOFINE$ is the assumption that the conditional independence relations that hold in a probability distribution over observed variables are a consequence of the causal structure alone, rather than a consequence of a particular choice of values for the causal parameters. In other words, it is the principle of no fine tuning, or faithfulness, which is one of the basic assumptions of causal discovery algorithms.

Thus, taking the two postulates of Non-locality and No signalling as a starting point, the argument is not the simple one we saw earlier, namely:

1. Non-locality
2. No-signalling.

Therefore, indeterminism.
But rather.

1. Non-locality
2. No-signalling

Therefore, either $\neg CAUSAL$ or $\neg NOFINE$ or $\neg IND$.

The consequence of Wood and Spekkens' result is then that the only way to explain the quantum correlations with a causal model while respecting independence of measurement outcomes and no-signalling, is to employ a causal model which is fine-tuned. Such fine-tuned causal explanations include Bohm's interpretation, as well as interpretations based on super determinism or retro-causality. What Wood and Spekkens' theorem shows is that the consequence of holding onto $NOFINE$, while also maintaining IND ,

Non-locality and No-signalling, is not indeterminism, as we have defined it above, but $\neg CAUSAL$.

It is now time to examine the relationship between determinism and $\neg CAUSAL$. As we saw above, as well as a causal structure represented by a DAG, causal models contain a set of causal parameters that specify the conditional probabilities between a variable and its parents. If the relationship between a variable X and its parents $\{Y_1, \dots, Y_n\}$ is deterministic, then $p(X|Y_1, \dots, Y_n)$ is either zero or one. Thus, a causal model in which the variables are determined by, as opposed to just being probabilistically related to, their parents is a special case of causal models in general.

Giving up on $CAUSAL$ means giving up on any causal model of quantum correlations which satisfies the causal Markov condition. Giving up determinism is not sufficient, because the result also rules out causal models which contain indeterministic relations between variables. Giving up on any causal models at all, particularly by rejecting Reichenbach's principle of the common cause, is a possible response to Bell violations which has been explored (eg. van Fraassen (1982), Hofer-Szabo, Redei, and Szabo (2013)). It is however a more general response than what appeared to be intended by the information theoretic interpretation. Bub's idea that intrinsic randomness is the critical central feature of the new information-theoretic structure appears to have been lost.

Another possibility is that what Bub has in mind with 'intrinsic randomness' is in fact not what I defined in section 3.3.1, but is in fact better explicated as $\neg CAUSAL$. In that case, Wood and Spekkens' result would provide an argument for 'intrinsic randomness', based on the basic principles of nonlocality and no-signalling. But then it is not so clear that such a position would provide any dissolution of the measurement problem. The correct conclusion of the Wood and Spekkens theorem is not that there can never be any causal explanation of any quantum measurement, but that the particular correlations giving rise to the Bell inequalities cannot be given a causal explanation. This has no impact on whether there is a causal model of the measurement process where there is only one party and one setting involved.

Overall then, we have not managed to find an argument for intrinsic randomness from principles.⁵ There is such an argument for unpredictability, and we then explored the possibility of a more indirect argument for intrinsic randomness, based on the desire to provide an explanation of the unpredictability which is not fine-tuned. However, in this case also, the consequence did not turn out to be intrinsic randomness after all.

Indeed, recent reconstructions of quantum theory in terms of axioms do not point to indeterminism as the key feature of the new information-theoretic structure. Rather quite a different message appears to be emerging from the reaxiomatisation programme. For example, Koberinski and Mueller suggest that 'Continuous reversible transformations, which can either be interpreted as computational processes or physical time evolutions, play a major role in singling out quantum theory from the space of GPTs. This indicates that interaction and reversibility of dynamics may be physically characteristic of quantum theory' (Koberinski and Mueller (2017), p. 12). The attempt to get at what reconstructions are really telling us about quantum theory is an ongoing effort.

4. Conclusion

Jeff Bub's efforts to develop an information-theoretic interpretation represent a serious attempt to understand how the insights

⁴ The CMC is the following. Let G be a causal graph with vertex set V and P be a probability distribution over the vertices in V generated by the causal structure represented by G . G and P satisfy the Causal Markov Condition if and only if for every W in V , W is independent of its non-descendants, given its parents.

⁵ Though to quote Hume, 'It would be inexcusably arrogant to conclude that because I haven't discovered a certain argument it doesn't really exist' (Hume (1748), 4.2).

from the quantum reaxiomatisation programme might bear on the traditional task of interpretation of the theory. The main theme has been the idea that the reaxiomatisation of the theory in information-theoretic terms might remove or dissolve certain explanatory demands that realist interpretation is usually taken to place. This dissolution would be motivated not by general antirealist scruples, but by principled arguments.

All the arguments for the information theoretic interpretation have taken inspiration from an analogy with the role of Einstein's derivation of special relativity from postulates in the interpretation of that theory. Different versions of the argument may be distinguished depending on exactly what the key lesson of Einstein's theory is taken to be. In the first version, the idea was that establishing a theory is a principle theory in Einstein's sense is in itself enough to provide an interpretation. This was followed by an argument that the principle theory establishes a kind of in principle underdetermination which renders certain kinds of interpretative approaches to quantum mechanics untenable.

In more recent years, a more sophisticated view has been developed, offering the following picture. It is possible for developments in physics not only to give rise to new explanations of certain phenomena, but also to change the explanatory landscape by making certain kinds of explanations redundant. The case of special relativity provides a canonical example of this kind of explanatory displacement. Special relativity brought a new understanding of space and time, which rendered certain kinds of constructive or dynamical explanations no longer necessary. Whereas Lorentz had been searching for a dynamical explanation of Lorentz covariance, Einstein replaced this with a different kind of explanation that was kinematic, rather than dynamic. The new space-time itself *replaces* part of the constructive explanation that Lorentz sought. For example, length contraction in special relativity can be explained as a feature of the structure of the new space-time. What makes the explanatory displacement work in the case of special relativity is the clear explanation of the feature of the new space-time, namely relativity of simultaneity, on the basis of principles. According to the information-theoretic interpretation, a similar explanatory displacement can be seen in quantum mechanics with the advent of a new understanding of the information-theoretic structure of correlations. Certain aspects of measurement are then seen simply as a feature of the new information-theoretic structure, rather than as requiring a dynamical explanation. Again, what would make the explanatory displacement work would be a clear explanation from principles of the key features of the new information-theoretic structure.

Even if one accepts that an explanatory displacement occurred in special relativity, and that it could in principle be replicated in quantum theory, a key question is whether we actually do have in the quantum case the kind of principle theory derivation that characterised special relativity. In that case, as we have seen, what clearly emerged from the principle theory approach was an identification of what background metaphysical assumption (absolute simultaneity) would need to be given up in order to reconcile the postulates. The Minkowski space-time could then be seen as a codification of space-time structure under the assumption that simultaneity is relative and not absolute. The information-theoretic interpretation suggests that the analogue is intrinsic randomness. However, we have failed to find a suitable argument from the quantum reconstruction to support this conclusion.

However, the development of information-theoretic interpretations has led to a healthy exploration of ways in which the project of interpreting quantum theory can be connected to, or informed by ongoing work in the foundations of the theory. All too often, interpretation is taken to be the task, to be carried out by philosophers, of clothing the 'bare formalism' provided by

physicists, to make that formalism conceptually decent (e.g. [Albert \(1992\)](#), [Wallace \(2008\)](#)). But in quantum theory, the basis of the formalism itself is still being actively explored by physicists. Part of the drive to do so is to achieve a deeper understanding of the theory by illuminating where the theory falls in the space of possibilities and why. Another primary motivation is as a step towards further progress in physics, by looking for ways in which the theory can be unified with other important theories, such as general relativity. It is highly desirable that the interpretation project remains closely connected to these ongoing developments. The task of interpretation should not be seen as a relatively sterile exercise in philosophical window-dressing. Although the information-theoretic interpretations so far proposed have not succeeded in some of their more ambitious aims, they have at least shown that there are potentially fruitful ways in which quantum reaxiomatisations may impact upon interpretation of the theory. These may go well beyond providing merely instrumentalist interpretations, and should continue to be explored as the physics develops.

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