ON THE POSSIBILITY OF PROVIDING SATISFACTORY RECONSTRUCTIONS OF QUANTUM MECHANICS USING INFORMATION THEORETIC CONCEPTS

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Abstract. This essay consists of two main parts: In the first (Sec.1-2), I consider the challenges that an information theoretic reconstruction of quantum mechanics (QM) faces if it aspires to provide fundamental explanatory power. In the second (Sec.3), I sketch a scenario in which most of these challenges are met, as a proof of concept. In the first part, I argue that the main challenge for reconstructions with the above aspiration is to provide a constructive model in the sense of Einstein. In the second part, I argue that upon the assumption that QM is a theory developed by (a certain notion of) observers, there can be constructive models of QM involving classical information. Sec.4 finishes with a summary and conclusion.

1. Introduction

Given the various attempts to provide reconstructions of quantum mechanics on the basis of (quantum) information theoretic principles (e.g. (Hardy, 2001; Pawlowski et al., 2009; Clifton et al., 2003) and other references in text), it is reasonable to ask how satisfactory such reconstructions can possibly be. Any answer to this question obviously depends both on the notion of information involved and one's criteria to judge the merit of a set of axioms or principles, which I here refer to as "reconstructing set".

Regarding the former, I will use Timpson's distinction between everyday and technical information. Everyday information is information that is had by a person, an observer, and is associated with uncertainty about and knowledge of facts or events (Timpson, 2013, 11). Technical information, information$_t$, is by Timpson defined as "what is produced by an information$_t$ source that is required to be reproducible at the destination if the transmission is to be counted a success" (ibid., 22). It is a formalised concept used in mathematics and theoretical sciences with weak derivative links to the epistemic concepts characteristic of everyday information.[1] Importantly, information$_t$ comes with a type/token-distinction: "Pieces of information$_t$" are abstract

[1] The distinction into everyday and technical information is peculiar to Timpson and not canonical. It may be argued that all talk of information can be cashed out in terms of information$_t$. None of the results of this essay are, in principle, affected by such arguments.

types that are instantiated by tokens, physical systems in particular states. The amount of (classical) information$_t$ in some set of alternatives $\mathcal{A} = \{A_i\}$ moreover is quantified by the Shannon entropy, which, for a probability distribution $P(A_i) = p_i$ over $\mathcal{A}$ is defined as (Nielsen and Chuang, 2000)

$$H(\mathcal{A}) = -\Sigma_i p_i \log_2(p_i).$$

Regarding the latter, the criteria for successful reconstruction, the most important is, of course, that a reconstructive set actually achieves a formal derivation of the theory in question. However, not every formally successful reconstruction may count as a satisfactory reconstruction. For example, the corresponding reconstructive set may be thought to lack explanatorily power. Regarding "information sets" - reconstructing sets that involve information in either of the above senses -, I here concentrate on a necessary condition for a satisfactory reconstruction of quantum mechanics of which it has been argued that either no information set can satisfy it or at least that no information set proposed so far satisfies it. This criterion is the following.

CC: An information set should provide a constructive model.

Call this the "constructivity criterion" (CC). The next section will introduce it in more detail and survey how some existing information sets are seen fail to satisfy it.

2. The challenge for information sets

2.1. **Principle and constructive theories.** Einstein introduced the distinction between principle and constructive theories into the philosophy of science. In the succinct words of Howard (2014)

> "[a] constructive theory, as the name implies, provides a constructive model for the phenomena of interest. An example would be kinetic theory. A principle theory consists of a set of individually well-confirmed, high-level empirical generalizations. Examples include the first and second laws of thermodynamics."

This distinction should not be understood as establishing a logical disjunctive, but instead as providing two perspectives on theory development. Nevertheless, the explanatory ambitions of theories of the two types do, in Einstein's view, differ:

> "Ultimate understanding requires a constructive theory, but often, says Einstein, progress in theory is impeded by premature attempts at developing constructive theories in the absence of sufficient constraints." (ibid.)

CC, according to this characterisation, then says that information sets should provide constructive reconstructions of quantum mechanics as opposed to principled ones, the reason being that they provide larger explanatory power concerning the fundamental nature of some phenomenon of interest - what I refer to as "fundamental explanatory power". That is, even though principle theories may be very rich in explanatory power and in fact even be preferable on grounds of the explanations they provide,[2] only constructive models can produce "fundamental explanations" in which the explanantia cannot themselves be understood as the effects of underlying dynamics (which is, of course, not true of *every* constructive model) and hence not be replaced by an account these dynamics.

Clearly, whether there are reasons to believe that an information set can or cannot satisfy CC depends on the sense of information that is employed.

2.2. **CC for technical information: The type/token-distinction.** The main difficulty that information sets making use of technical information$_t$ face regarding CC is that they need to motivate the possibility of a constructive model that involves a type/token-distinction. The worry here goes as follows:

Types, pieces of information$_t$, are abstract. This is because they are abstract*ed* from all the *tokens* that instantiate a given type, where this process of abstraction can be represented, for example, by defining types as an equivalence class $[x]$ of tokens x instantiating it. For this reason, types are not fundamental in the sense of the last section: We can always replace explanations involving types together with laws formulated in terms of types by explanations involving all the tokens corresponding to these types together with laws formulated in terms of tokens. The converse, however is not true because we don't define a token in terms of types. Consequently, an information$_t$ set cannot provide a *constructive* model because it necessarily involves non-fundamental entities.

Note that the point of this argument is *not* that information$_t$ should be excluded from any constructive model simply because it involves *different* kinds of objects. Such an argument could not have much force in that paradigmatic constructive theories such as kinetic theory or Newtonian mechanics involve different kinds of objects - for example systems in states x, y - and two-place relations holding between them $R(x, y)$ - for example force. And while there is an open debate concerning the explanatory status of such relations, a radical reductionist position that ascribes fundamental explanatory power only to theories with a single kind of object would

[2]Think of the case of providing an explanation whether a cube fits through a hole in a screen. Here, an explanation in terms of the size of the cube and hole is preferable over the more "fundamental" explanation in terms of the Standard Model according to most standard.

seem to be an unjustifiedly strong one to take (Woodward, 2014). Similarly, it would seem too strong to reject a model as unconstructive simply because it employs relations between different types (in the set-theoretic, not the information-theoretic sense), i.e. $R(X, x)$, where X and x are of a different type.

The criticism instead is that because (a) laws using information$_t$ will involve relations of the form $I_t([x], y)$ between an information-theoretical type $[x]$ and a physical system in state y, (b) any such law can be re-expressed as a (set of) law(s) involving (a) relation(s) of the form $R(x, y)$ and (c) only laws involving relations between states of physical systems have *fundamental* explanatory power, no model using can information$_t$ can provide a constructive model.[3]

Thus, an information$_t$ set that is to provide a constructive model must adequately[4] justify the fundamentality of types, pieces of information in this model in the sense that dynamics involving pieces of information cannot be replaced dynamics involving only tokens.

Timpson (2013) implicitly seems to make this worry the basis for his criticism of some of the existing accounts in information theoretic reconstructions, for instance Zeilinger's Foundational Principle (Zeilinger, 1999).[5] This principle, in one of its formulations, states that

> **FP:** An elementary system carries one bit of information.

From it, Zeilinger, for example, "reconstructs" the randomness of quantum theory by, roughly speaking, contrasting the large number of questions that can be asked about any elementary system with the single answer that can be encoded in its state. What is important for us here is the lack of explanatory power attested Zeilinger's approach by Timpson (2013, Ch.8). With respect to the derivation of randomness, for example, he finds that FP does not explain "*why* the state of an elementary system cannot specify an answer to all experimental questions that could be asked [...] The Foundational Principle says nothing about the structure of the set of experimental questions" (ibid., 155, orig.emph.). Underlying this criticism we recognise the CC: The Foundational Principle functions *principle*-theoretically in that its statement involves an effect, in Timpson's view, of some underlying dynamics, and does not explain them. In other words, its formulation in terms of information limits, applying at the level of types, Timpson

[3] The same criticism applies to a relation between types such as $I_t([x], [y])$ that can be replaced by relations $R(x, y)$.

[4] Adequacy here means, for example, that information should not be treated as a kind of substance (Timpson, 2013, Ch.2).

[5] On similar grounds he criticises Rovelli's relational quantum mechanics (Rovelli, 1996), whose information principles are

> R1 There is a maximum amount of relevant information that can be extracted from a system,
> R2 It is always possible to acquire new information about a system.

takes to be the result of the dynamics governing whatever physical system it is that instantiates these limits at the token level - and thus concludes that the principles have no fundamental explanatory power.

2.3. **CC for everyday information: Bell's questions.** The implications of CC for the everyday sense of information take a different form. As introduced, everyday information is tightly linked to the notion of an observer that has information about the world. Based on this link, I can see at least three different reasons that have been suggested to bar everyday information from figuring in constructive models:

1. The point of physics. Consider the following quote by Einstein:

> Physics is an attempt conceptually to grasp reality as something that is considered to be independent of its being observed. In this sense one speaks of "physical reality" (quoted in (Timpson, 2013, 45)).

What is suggested here is that it is not the *job* of physics to produce observer-dependent accounts of the world. Reconstructions of some theory of physics in terms of observer-dependent concepts therefore render this theory "unphysical" in a sense.

2. Imprecision. Bell believed that everyday information cannot figure in a constructive model, because the notion of an observer would be incompatible with a *precise* formulation of physical phenomena (Bell, 1990, 34). There are, I think, two aspects to this imprecision: First, literally as a difficulty of giving a precise definition of what an observer is and what it is not. Second, just like in the case of types in the last section, that they are not fundamental; that it should be possible to phrase any observer-dependent formulation of physics in terms of an observer-independent one. Why so? The obvious answer, from the point of view of the CC is: Because any acceptable definition of observers in physics should come in terms of physical systems that are not themselves observers and hence any description of physical phenomena involving observers should be substitutable by one that does without them.[6]

3. Intentionality. Everyday information is *intentional*, i.e. it is a mental concept that has the property of being "about" something. Concerning reconstructions of quantum mechanics, Timpson (2013, 146pp.) argues that it is difficult to see what any information could there be about. In particular, he considers the common case in which it is the quantum *state* is meant to

[6]Note that this reasoning is independent of one's position towards the status of laws, whether for example they exist observer-independently or not.

encode the information of an observer. Here, Timpson sees two kinds of things that information encoded in the quantum state of a system could reasonably be about, namely

(1) information about how things are with a system prior to measurement, i.e. about hidden variables.
(2) information about what the outcomes of experiments will be,

Concerning the first, Timpson thinks that such a move is question-begging in that the aim of the information principle account was to do away with physical hidden variables in the first place. Now, while it is true that from theorems such as the Kochen-Specker theorem (Kochen and Specker, 1967) or the Bell inequalities (Bell, 1964) we know that any such hidden variables would have to behave funnily and it may be preferable to do without them, Timpson's verdict certainly does not amount to barring everyday information from reconstructions of quantum mechanics by virtue of its intentionality. However, the recent PBR theorem allows for a stronger conclusion concerning the first option: This theorem rules out the consistency of any epistemic hidden variable theory (eHVT) that assumes preparation independence with quantum mechanics (Pusey et al., 2012). eHVTs are theories in which the quantum state is taken to represent an observer's knowledge of the underlying but hidden ontic state of a system, for example Spekkens' toy model (Spekkens, 2007). But this is just what the first option amounts to. Thus, by the PBR theorem, no constructive model in which everyday information is interpreted as being about hidden variables that are also elements of this model can possibly reconstruct all of quantum mechanics, putting a stop to the first option.

Concerning the second, this information could be either about experiments on many systems, encoding outcome statistics, or single systems. If it is the former, then a reconstruction in terms of it necessarily involves a form of instrumentalism that doesn't provide the fundamental explanatory power sought; but it can also not be the latter, argues Timpson, because in the absence of hidden variables observers can ascribe different states to the same single system (for example in the "Wigner's friend" scenario) and this clashes with the *factivity* of information, the property that one can only have information about some p if p is indeed the case. Granting that instrumentalism is indeed not providing the explanatory power we're seeking, the only remaining strategy along the second option seems to be to provide a scenario in which the quantum state represents factive yet observer-dependent pieces of information, i.e. one in which observers may assign different states to the same single system without thereby violating factivity. It is difficult to see how else a quantum state could be factive and not referring to hidden variables.

Finally, it may be that Timpson's list is not exhaustive. But what other options should there be? The information in the quantum state either refers to something observable or something unobservable - and quantum mechanically the latter corresponds to hidden variables and the former most generally to measurement outcomes.

2.4. **Summing up.** Thus, this is the challenge that CC sets for an information theoretic reconstruction of quantum mechanics: Any information$_t$ set needs to (at least) motivate the fundamentality of types, while any information set involving everyday information needs to (at least) (1) justify the relevance of observers for doing physics, (2) provide an account of observers that is precise and (3) give an observer-dependent and factive account of what the quantum state is about. In the remainder of this essay, I present an account that involves both technical and everyday information and, so I argue, may meet these challenges except for (1).

3. Sketch for a proof-of-principle-solution

3.1. **A sufficient condition for the relevance of information.** Consider the following passage in Rovelli (2015, 79):

> [Information] is relevant in physics when it refers to an interaction between two systems where the effects of the interaction on the second depend only on few variables of the first, and are independent of the rest of the variables.

The sense of information Rovelli alludes to is explicitly the technical and not the everyday sense. That it is not the everyday sense is implied by the independence of the notion of an observer - information can be relevant when no observers are around. That it is the technical sense becomes clear once we see that it relates directly to Shannon entropy. Rovelli does not make his idea much more specific but I take it he has the following in mind: In the scenario described by Rovelli, in which only a small subset of the degrees of freedom of one system determines its interaction with a second, many different states of the first system lead to the same interaction effects. Consider, for example, two interacting classical systems A, B with two and four distinguishable states respectively. Say the post-interaction state of A is determined completely by the pre-interaction state of B, in particular such that if the B is in one of the first three states, A will end up in its first state, while the fourth state of B has A evolve into its second state. Then if B is initially prepared as a mixture with probabilities $\{\frac{1}{8}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}\}$ over the four states, then the post-interaction state of A is a mixture with probabilities $\{\frac{1}{2}, \frac{1}{2}\}$. In this example, which fits Rovelli's quote, the Shannon entropy is relevant for a description of the interaction in several ways. For example, the fact that the behaviour of A is completely determined by the state of B is captured by the fact that $H(A, B) = H(B)$ and consequently the "mutual information" is $H(A; B) := H(A) - H(B) - H(A, B) = H(A)$ is a function of $H(A)$ only. Similarly, the conditional entropy $H(B|A) := H(A, B) - H(A) = H(B) - H(A)$ quantifies the sensitivity of A to the full state of B and thus will be a relevant for laws governing their interaction.[7]

Thus, what Rovelli seems to point out is that the Shannon entropy captures the many-to-one relationship between pre- and post-interaction states of interacting systems and that this makes information$_t$ a relevant quantity in the description of, for example, the interaction dynamics. However, information$_t$ here is relevant only because it provides an *economic* description of such dynamics, not for any fundamental explanatory power it adds. Indeed, the above example illustrates exactly the point of sec.2.2: A fundamental explanation of the interaction involves only the actual states of A and B, and does without Shannon entropy.

3.2. **Meeting the CC for technical information.** [8]

The main idea of my suggestion in order to get around this "problem" is to connect Rovelli's scenario to everyday information. In particular, the aim is to define observers such that in their description of the above processes the Shannon entropy cannot be substituted by a description of underlying states and therefore appears fundamental.

Conceptualising system A from the example above as an observer, it may seem suggestive to carry out this idea by defining observers as finite-dimensional physical systems with a supervenient mental state and then to argue that the two-dimensionality of A bars her from ever mentally representing the actual state of B. For this reason the *value* of the Shannon entropy would enter a description of the interaction from the perspective of A as a fundamental quantity that cannot be replaced by the "full" story simply because the fact that $d_A < d_B$ renders A unable to mentally produce such a stroy. Even though this is merely a sketch of carrying out the main idea, it is clear that such an account is a non-starter for QM. This is because QM allows for the description of systems whose dimension is much smaller than that of any system with a mental state that could make for an observer. Hence the limitation of the observer can simply not be the fact that his dimension is lower than that of the systems she describes.

[7]In the special case, in which B is prepared with uniform weights, these quantities can be represented by state space volumes over the uniform Lebesgue measure, as for example in the case of statistical mechanics, where the conditional entropy above corresponds to macrostate phase space volumes (Nielsen and Chuang, 2000).
[8]Everything in this section goes beyond Rovelli's account in his (2015).

Still, it is possible to develop a valid quantum version along similar lines: First, adopt for the sake of argument an Everettian ψ-realist view according to which the closed evolution of some physical system B is represented by solutions $|\psi(t)\rangle \in \mathcal{H}_B$ of the Schrödinger equation, where $\mathcal{H}_B$ is the Hilbert space of B.[9]

Secondly, define the following notions:

Definition 3.1 (Observer)**.** *An observer is a finite-dimensional quantum system A with a mental state that supervenes bijectively on her physical state.*[10]

Definition 3.2 (Measurement)**.** [11] *Given an observer A and a quantum system B in state $|\psi\rangle = \Sigma_{i=1}^{d_B} \alpha_i^m |m_i\rangle, \quad \langle m_i|m_j\rangle = \delta_{ij}$, a measurement of property m by A on B is an interaction between A and B such that, for some ready state $|a_m\rangle$,*

$$|a_m\rangle \otimes |m_i\rangle \xrightarrow{SE} |a_{m_i}\rangle \otimes |m_i\rangle \equiv |a_{m_i}, m_i\rangle$$

Now, given any measurement of some m by an observer A on a quantum system B, information will be relevant in the following way: The dimension of A that is required for her to exhibit a supervening mental state makes her extremely sensitive to decoherence, internally and also with the environment, in the standard fashion (Zurek, 1981): For an environment with initial state $|E_0\rangle$ such that the Schrödinger equation (SE) gives $E_0 \otimes |a_i\rangle \xrightarrow{SE} |E_i\rangle \otimes |a_i\rangle$ for any state $|a_i\rangle$ of A and $\langle E_i|E_j\rangle = \delta_{ij}$, the measurement process above is described as

$$\begin{aligned} &|E_0\rangle\langle E_0| \otimes |a_m\rangle\langle a_m| \otimes |\psi\rangle\langle\psi| \\ &\qquad \xrightarrow{SE} \Sigma_{i,j} \alpha_i^m (\alpha_j^m)^* |E_{m_i}\rangle\langle E_{m_j}||a_{m_i}, m_i\rangle\langle a_{m_j}, m_j| \\ &\qquad\qquad \xrightarrow{Tr_E} \rho_m \approx \Sigma_i |\alpha_i^m|^2 |a_{m_i}, m_i\rangle\langle a_{m_i}, m_i|. \end{aligned}$$

This process describes the effect which the measurement of B by A has on their joint system. There are several many-to-one relations that are apparent here and for, by Rovelli's suggestion,

[9]Making such an assumption is *not* begging the question because the point of these considerations is to motivate the possibility of information as being fundamental and thereby allowing for a constructive model of quantum mechanics. This is consistent with assuming that certain elements of quantum theory, i.e. unitary evolution and the possibility of superpositions, are *not* fundamentally related to information in any way. Of course, a more extreme position that attempts to reconstruct quantum mechanics purely based on information theory, it-from-bit-style, cannot make such an assumption.

[10]The bijective relation between physical and mental states I introduce for mere convenience, namely in order to avoid "mental degeneracy" in the sense that different post-measurement states $|a_{m_i}\rangle$ produce the same mental state. A slightly more sophisticated account should be able to make the exact same argument without bijectivity and simple superveneience. (McLaughlin and Bennett, 2014)

[11]Both measurements and decoherence effects are here idealised as non-disturbing. As in the case of observers, a more sophisticated account can cover for more general scenarios.

information concepts can be used to describe each of these. For example, there are observer-states that instantiate the same ready-state $|a_m\rangle$ or quantum states that produce the same ρ_m (i.e. states equivalent up to phase factors). The one that, I argue, becomes *fundamental*, however, is given by $H(\{|\alpha_i^m|^2\}) = -\Sigma_i|\alpha_i^m|^2\log_2(|\alpha_i^m|^2) \approx S(\rho_m)$, where $S(\rho) := -tr[\rho\log_2(\rho)]$ is the *von Neumann entropy*, which is the quantum generalisation of the Shannon entropy but for ρ_m measures only classical information. The sense in which $S(\rho_m)$ is fundamental is in *quantifying the deviation in the evolution of the state of B due to the measurement interaction.* That $S(\rho_m) = S(Tr_A(\rho_m))$ can be interpreted as such a measure of deviation is seen, for example, by recognising that

$$(1) \qquad |\alpha_i^m|^2 = \langle\psi|m_i\rangle\langle m_i|\psi\rangle = 1 - \delta(|\psi\rangle\langle\psi|, |m_i\rangle\langle m_i|)^2,$$

where $\delta(\rho, \sigma)$ is the trace distance (Nielsen and Chuang, 2000). (1) implies that the weights in the entropy are directly linked to how the elements of the mixture in the decohered state differ from $|\psi\rangle$.

As such, $S(\rho_m)$ will be relevant in the formulation of laws describing the evolution of quantum systems that interact with observers. Of course, such laws need not be fundamental in that, at the level of the full wave function, a complete description of the process without decoherence can be given. The fundamentality enters with the following assumption:

> **QM as observer-theory (QMOT):** Quantum mechanics is a theory of the behaviour of quantum systems as they appear to observers, where how "a system B appears to an observer A" is given by the mental state that supervenes on the post-measurement state of A in a measurement of B.

Now, it is clear from $\rho_m \approx \Sigma_i|\alpha_i^m|^2|a_{m_i}, m_i\rangle\langle a_{m_i}, m_i|$ that B can only ever appear to A in terms of the mental state supervening on the states $|a_{m_i}\rangle$ that correspond to the system's states $|m_i\rangle$. But since, in general, $|m_i\rangle \neq |\psi\rangle, \forall i$, the quantity $S(\rho_m)$ will *always*be relevant in a theory of B that is produced by A. Furthermore, it will be fundamental because *to* A, the fundamental explanation in terms of the joint system's full unitary evolution is inaccessible. This is not because of some vague notion of "impossibility of self-reference", "relationalism" or "irreducibility of mental states", but simply because of the size of A that keeps her in a decohered state.

In this way, I suggest, could the presence of pieces of information$_t$ as fundamental types in a constructive model of QM may be motivated.

Some remarks:

(1) The relevant information here is *classical* and is meant to necessarily enter the formulation of an observer's quantum theory based on her effective *classicality*.
(2) Care has been taken not to assume the Born rule: The weights $|\alpha_i^m|^2$ are *not* interpreted as probabilities: They are trace-distance weights for the alternative outcomes $|m_i\rangle$, each of which is, under this interpretation, in fact assigned an *equal a priori* likelihood of occurring!
(3) Nor are the $|\alpha_i^m|^2$ statistical: They apply to the measurement of a *single* system. Of course, A could tomographically derive the value of $S(Tr_A \rho_m)$, but here the $|\alpha_i^m|^2$'s appear as frequentist probabilities and thus don't provide an explanation of the $|\alpha_i^m|^2$'s as I interpret them.
(4) Nothing in this essay is meant to motivate QMOT, nor its necessity for a constructive model of quantum information. The aim is merely to present *one* set of assumptions to produce such a model, as a proof of concept. In fact, by building on Rovelli's explicitly observer-*in*dependent notion of information, the argument presented here undermines some of the *abductive* arguments that infer from the successful application of information theory in physics research the necessity of an observer.
(5) The account was, as a working assumption, set up from the view of an Everettian ψ-realism. Is it bound to come with it? I take it that the above could be reformulated in any interpretation according to which there exists an observer-independent matter of fact about the state $|\psi\rangle$, although my proof-of-concept-ambitions would be fulfilled even if only Everett worked.

3.3. **Meeting the CC for everyday information (almost).** Remember that the arguments against the possibility of a constructive model involving information in the the everyday sense consisted in (1) the observer-independence *per definitionem* of physics, (2) the imprecision of observers and (3) its intentionality.

Of course, in assuming QMOT the proposal discussed in this section cannot answer the first of these (cf. remark (4)). However, regarding (2) I take observers here to be sufficiently precisely defined: They are quantum systems - subject to the same laws as all others - that happen to have supervenient mental states. Their decohering effect they share with other similarly large systems whether or not those have mental states. Admittedly, both decoherence and the emergence of mental states come in degrees. But this does not preclude the possibility of a precise description of these effects.

Concerning (3), things are a bit tricky: We can say exactly what the fundamental pieces of information, quantified by $S(\rho_m)$ are about: The disturbance of a system given its measurement by the observer. This information is factive (in that it completely determined by $|\psi\rangle$ and m), observer-dependent (in that it depends on the choice of m) and about single systems. As such, it is exactly of the kind that was required to interpret information of quantum states as being about measurement outcomes. However, I have said nothing about how this information should be represented in a state, let alone a *quantum* state. Let me therefore now say how, I think, linking $\mathcal{S}(\rho_m)$ to the quantum state of A's theory in a way that preserves the above three characteristics is possible in principle:

A can encode the relative frequencies for outcomes to all measurements $\{m\}$ on N systems in state $|\psi\rangle$ in a "statistical quantum state" $|\psi(N)\rangle_A$. By assuming a rule BR that links outcome frequencies to trace distance between the post- and pre-measurement (effectively a Born rule)[12], she can then interpret $|\psi(N)\rangle_A$ as the quantum state of B or any other of the single systems. This state would in her theory both be *factive information* about outcomes on many system (falling prey to Timpson's instrumentalism) *and*, via BR, her *non-factive degree of belief* about the disturbance of a single system B's state as a result of her measurement of it.

Now, unlike a Quantum Bayesianist picture in which $|\psi(N)\rangle_A$ is as good as it gets, this degree of belief here can, as a matter of fact, be false or correct, for the cases in which $|\psi(N)\rangle_A$ is equal to $|\psi\rangle$ or not respectively. For this reason A could, in principle, devise a test to check for this equality, using for example the fact that $\lim_{N\to\infty} |\psi(N)\rangle_A = |\psi\rangle$. In this way $|\psi(N)\rangle_A$ could turn into a *factive* piece of information.[13] In this case, $|\psi(N)\rangle_S$ would inherit its factivity, observer-dependence and relation to single systems from the fundamental pieces of information $S(\rho_m)$ and satisfy (3). Of course, whether this move from degrees of belief to information is kosher is contentious, but I don't think it is clear that it must be impossible. In any case, even if the quantum state $|\psi(N)\rangle_A$ in A's theory itself ends up not representing fundamental information, this does not affect the independent point that a constructive model of A's quantum theory would fundamentally involve information.

[12]*Pace* my earlier remark about not assuming the Born rule, this BR-rule would be assumed *by* A and not be true observer-independently!

[13]Note that this does not affect the fundamentality of $S(\rho_m)$: It was fundamental not in the sense that its value could not be derived from another quantity, the quantum state, but that it could not be replaced by a non-decohering story of the measurement dynamics involving A herself.

4. Summary and Conclusion

Summing up, in this essay I have first investigated the challenges that information theoretic reconstructions of theories in physics, and in particular quantum mechanics, face. Requiring them to provide the fundamental explanatory power that only constructive models can provide was seen to impose severe challenges on both technical and everyday information. In the second part of the essay I have sketched an account that, as a proof of concept, is meant to deal with most of these challenges. In assuming that quantum mechanics is a theory developed by precisely defined observers, I showed that classical information about the disturbing effect of measurement interactions is fundamental in such an observer-theory and that it is, in principle, possible for this information to be encoded in a quantum state such that it survives the problems discussed by Timpson. This sketch, I think, illustrates both, on the one hand, the difficulty of producing a fundamentally explanatory information theoretic reconstructions of quantum mechanics as well as, on the other, its possibility in principle.

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