To appear in *British Journal for the Philosophy of Science*

Is Standard Quantum Mechanics Technologically Inadequate?

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Thursday 1 June 2006

Abstract. *In a recent issue of this journal, P.E. Vermaas [2005] claims to have demonstrated that standard quantum mechanics is technologically inadequate in that it violates the 'technical functions condition'. We argue that this claim is false because based on a 'narrow' interpretation of this technical functions condition that Vermaas can only accept on pain of contradiction. We also argue that if, in order to avoid this contradiction, the technical functions condition is interpreted 'widely' rather than 'narrowly', then Vermaas his argument for his claim collapses. The conclusion is that Vermaas' claim that standard quantum mechanics is technologically inadequate evaporates.*

Contents

1 Introduction

In a provoking paper, Vermaas [2005] addresses the problem of how to select the best interpretations of quantum mechanics from available ones: which conditions must an interpretation of quantum mechanics meet? Interesting question. Call this problem the *selection-problem* and such conditions *interpretation-conditions*. (Of course an article if not a book could be written on the distinction between the theory of quantum mechanics and an interpretation of quantum mechanics; we follow however Vermaas and take the distinction for granted.) By *quantum mechanics and its standard interpretation*, briefly *standard quantum mechanics* (SQM), we and Vermaas [2005, p. 637, fn. 2] mean quantum mechanics *with* the projection postulate (Dirac, Von Neumann), *with* the standard property postulate (Dirac, Von Neumann), but with nothing else.

The *standard property postulate* ('eigenstate-eigenvalue link') of SQM provides us with a condition (which is both sufficient and necessary, hence a criterion) for the ascription of physical properties to a physical system, depending on its physical state: a physical system possesses quantitative physical property $a \in \mathbb{R}$ associated with physical magnitude $\mathcal{A}$, denoted by $\langle \mathcal{A}, a \rangle$, — or what we take to be same: $\mathcal{A}$ has value a — iff the physical state of the system corresponds to an eigenstate of eigenvalue a of the operator A that represents $\mathcal{A}$. Thus we emphasise that the ascription of *physical properties* and the ascription of a *physical state* to every physical system are sharply distinguished; the standard property postulate says there is a particular logical relation between these ascriptions.

The first two interpretation-conditions that Vermaas addresses are *logical adequacy* and *empirical adequacy*, that is to say, the interpretation must not lead to contradictory statements and it must not lead to statements that are in conflict with established experimental results, respectively. A third interpretation-condition, which has nothing to do with empirical adequacy and is, surprisingly, not mentioned by Vermaas, is that the interpretation should solve or dissolve the measurement-problem. All available interpretations of quantum mechanics certainly (are supposed to) meet the first two conditions, and very likely also the third condition in one way or another, which makes these three interpretation-conditions useless in order to achieve any progress towards a solution of the selection-problem. Vermaas now proposes what we shall call the condition of 'technological adequacy' as a useful condition in this regard. The condition of *technological* *adequacy* is a pragmatic condition that consists of the conjunction of two other conditions, the 'technical functions condition' and the 'engineering sketches condition'.

Vermaas [2005, p. 653] exerts extreme caution in judging SQM by the lights of the 'engineering sketches condition' and ends a discussion of its possible relevance in the context of a scanning tunneling electron microscope with the remark that one can "reject this condition altogether" by considering the engineering sketches condition as serving only heuristic purposes. Then necessarily all help in solving the selection-problem by means of the condition of technological adequacy must come from its other conjunct, the technical functions condition. Thus we direct our attention to this technical functions condition, as Vermaas also does. Vermaas [2005, p. 645] formulates it as follows:

> **Technical Functions Condition.** Interpretations of quantum mechanics accommodate the ascription of technical functions ϕ to technical artefacts described by quantum mechanics, by reproducing the physical conditionals $\phi : \mathcal{C}_j \to \mathcal{R}_j$, $j = 1, 2, \ldots$, entailed by these function ascriptions.

These conditionals are *subjunctive*, as Vermaas indicates in a footnote [2005, p. 644, fn. 9]; we denote these *technical function conditionals*, or *tf–conditionals* for short, symbolically as follows (τ is an artefact):

$$\textbf{tf–conditional:}\quad \tau \textit{ in circumstance } \mathcal{C}_j \quad \Box\!\!\rightarrow \quad \tau \textit{ exhibits or produces result } \mathcal{R}_j \;. \qquad (1)$$

Vermaas [2005, p. 646] his central and provoking claim is the following one.

> **Inadequacy Claim.** Standard quantum mechanics (SQM) is technologically inadequate in that it does not satisfy the Technical Functions Condition. Specifically, there is an experiment, a so-called teleportation experiment, that involves a technical artefact whose tf–conditional (1) SQM cannot 'reproduce', so that SQM does not meet the Technical Functions Condition and therefore is technologically inadequate.

Our critique is organised as follows: in Section 2, we consider a 'narrow interpretation' of the tf–conditionals (1), which Vermaas claims to use but actually violates in his illustrations and arguments; in Section 3, we consider a 'wide interpretation' of the tf–conditionals (1) and argue this is really the only other interpretation left to consider in the context of quantum mechanics; in Section 4, we argue that Vermaas' argument of his Inadequacy Claim breaks down; in Section 5, we draw a conclusion and briefly address the alternative interpretations of quantum mechanics that Vermaas also briefly addresses.

2 The Narrow Interpretation

Vermaas [2005, pp. 644–5] urges that both physical circumstances $\mathcal{C}_j$ and results $\mathcal{R}_j$ in the tf–conditionals (1) should be taken as *physical properties*, in the sense of values of physical magnitudes that are mathematically represented in SQM by operators acting on the state-spaces of the relevant physical system (not necessarily but generically the artefact τ). This is how one standardly talks about properties and property-ascriptions in the context of quantum mechanics (cf. Vermaas [1999], *passim*, [2005, p. 638]); we follow suit. Call this the *Narrow Interpretation* of (1).

In the first quantum-mechanical example of an artefact that Vermaas provides, he already breaks out of his own Narrow Interpretation. This example concerns a piece of measurement apparatus, call it μ. The technical function ϕ_μ of μ, when it measures (discrete) physical magnitude $\mathcal{A}$ of physical system σ, is to exhibit, after σ has interacted with μ, a number $a \in \mathbb{R}$ that is the value of $\mathcal{A}$ when S is in pure physical state $|\psi\rangle$. The relevant tf–conditional for pure states is (Vermaas [2005, p. 645]):

$$\text{incoming state } |\psi\rangle \;\; \Box\!\!\rightarrow \;\; \text{outcome } a_k \text{ with prob. } |\langle a_k|\psi\rangle|^2. \tag{2}$$

(Notice that the antecedent of (2) is about physical system σ and the consequent about measurement-apparatus μ, which is not displayed. Let that pass. Vermaas surely means 'relative frequency' rather than 'probability', because relative frequencies are empirical but whether probabilities are empirical is a controversial issue. Let that pass too.) Conditional (2) breaks out of the Narrow Interpretation in three ways: (i) there is no ascription of a physical *property* but of a physical *state* in the antecedent, which very well can be a superposition of eigenstates of operator A so that, by virtue of the orthodox property postulate, σ does not have any of the relevant physical properties; (ii) the *same* antecedent can give rise to *different* consequents, something that was not announced as a possibility in the Technical Functions Condition; and (iii) probabilities are mentioned, something that also was not announced as a possibility in the Technical Functions Condition.

Before we continue to show where else Vermaas breaks out of the Narrow Interpretation, we want to devote a few words to the following questions, which obtrude when reading Vermaas' tf–conditional (2). What if μ does not exhibit the value a_k from the spectrum of A with relative frequency $|\langle a_k|\psi\rangle|^2$? Does artefact μ then malfunction or is then quantum mechanics refuted? These questions strongly suggest that it would have been better to break tf–conditional (2) in two components.

The first component concerns the standard characterisation of a measurement apparatus of physical magnitude $\mathcal{A}$, call it $\mu(\mathcal{A})$, as an artefact having pointer-magnitude $\mathcal{M}$ and ready-state $|M_0\rangle$; its tf–conditional (for the pure case and a so-called *ideal sharp measurement*) is as follows:

$$\begin{gathered}\text{Composite system of } \sigma \text{ and } \mu(\mathcal{A}) \text{ is in state } |\psi\rangle \otimes |M_0\rangle \quad \Box\!\!\rightarrow \\ \mu(\mathcal{A}) \text{ exhibits values } m_j \text{ of } \mathcal{M}\text{, one-one correlated to values of } \mathcal{A}.\end{gathered} \tag{3}$$

The second component concerns the fact that SQM tells us that the correlated values of $\mathcal{A}$ belong to the spectrum of A, and that in a sequence of repeated measurements of $\mathcal{A}$, value a_k will be found with relative frequency $|\langle a_k|\psi\rangle|^2$. If tf–conditional (3) is violated (or better: if its implied indicative conditional is violated because only that implication is empirically accessible), then artefact $\mu(\mathcal{A})$ malfunctions, and then we cannot test quantum mechanics using $\mu(\mathcal{A})$; whereas if tf-conditional (3) is not violated, artefact $\mu(\mathcal{A})$ functions properly and we can test quantum mechanics: if the measured values correspond one-one to values that are not in the spectrum of A or the relative frequency of measured value a_k diverges from Born-measure $|\langle a_k|\psi\rangle|^2$, then quantum mechanics is in trouble, otherwise it is supported. We leave this issue now and move on to the experiment that plays the main part in Vermaas his argument for his Inadequacy Claim (cf. Section 1).

Vermaas [2005, pp. 646–51] considers a *teleportation experiment*: a quantum state of one physical system (particle 1, with its state space $\mathcal{H}_1$) is transferred to another physical system, particle 3 (so-called because there is another particle, labeled '2', that plays a rôle in the teleportation process); particles 1 and 3 do not interact. Let θ be the artefact that realises this process. The concomitant tf–conditional is (not explicitly stated, although implied by Vermaas [2005, p. 646]):

$$\text{particle 1 in quantum state } |\varphi\rangle \in \mathcal{H}_1 \;\; \Box\!\!\rightarrow \;\; \text{particle 3 in quantum state } |\varphi\rangle \in \mathcal{H}_3 \;. \tag{4}$$

We point out that here, again, Vermaas breaks out of his Narrow Interpretation on two accounts: both in antecedent and consequent there is no ascription of physical properties — but there is an ascription of physical states.

Vermaas [2005, p. 647] breaks out of his Narrow Interpretation once again when writing down the tf–conditional of a decoder D (which is part of the teleportation artefact θ) in his formula (2):

$$\text{incoming quantum state } |\psi_1\rangle\langle\psi_1| \otimes \tfrac{1}{2}\mathbb{1}_2 \quad \Box\!\!\rightarrow \quad \text{outcome } g_j \text{ with prob. } \tfrac{1}{4}\,. \tag{5}$$

Finally, Vermaas [2005, p. 650] does it again when he writes down the following tf–conditional, again attributed to the decoder D, in his formula (3):

$$\text{incoming state } |\psi_1\rangle\langle\psi_1| \otimes \tfrac{1}{2}\mathbb{1}_2 \quad \Box\!\!\rightarrow \quad \text{signal } s_j \text{ in } C \text{ with prob. } \tfrac{1}{4}\,. \tag{6}$$

We conclude that in his arguments and illustrations, Vermaas violates his own tf–conditionals when interpreted Narrowly; therefore he must interpret them differently. Next we consider different interpretations.

3 The Wide Interpretation

Call the interpretation of $\mathcal{C}_j$ and of $\mathcal{R}_j$ in the tf–conditional (1) as 'physical property or physical state' the *Wide Interpretation* of (1). Vermaas could easily accept the Wide Interpretation, because it seems exactly the right way to translate the general tf–conditionals (1) into the language of SQM.

Vermaas his general tf–conditional (1) emerges from the consideration that "artefacts have their function on the basis of their physical structure", and a technical artefact relates technical functions to "physical roles and input-output relations" (Vermaas [2005, p. 644]). Vermaas specifies this physical structure of the artefact in terms of *physical capacities* and the *ascription of physical conditionals*, whereby the last-mentioned is in turn specified as that the artefact will display or produce a certain *physical result* $\mathcal{R}_j$ under a certain *physical circumstance* $\mathcal{C}_j$. In order to avoid the usual trouble with indicative conditionals — known from discussions about dispositional properties such as solubility and observability —, the last specification leads to the subjunctive tf–conditional (1). Then, in the *very last step*, does Vermaas interpret physical circumstance $\mathcal{C}_j$ and result

$\mathcal{R}_j$ in the tf–conditional (1) as *physical properties* only, and thus he has adopted the Narrow Interpretation. If one adopts however the Wide Interpretation, only this *very last step* needs to be changed, in that one allows $\mathcal{R}_j$ and $\mathcal{C}_j$ to comprise also physical *states*. Physical properties or physical states: why throw one of them away in the very last step when entering quantum-mechanical territory? Is it not *prima facie* much more natural to allow them both to occur in tf–conditionals (1)? Vermaas provides no reason for his unexpected limitation to physical properties only.

Anyhow, our main criticism so far is *not* just Vermaas his slide into the Narrow Interpretation, but what we have pointed out in the previous Section: Vermaas accepts the Narrow Interpretation by his own words but he uses the Wide Interpretation in all his arguments and illustrations.

There seems, however, to be no reason for alarm. Vermaas can simply sail away from these contradictions by rejecting the Narrow Interpretation and accepting the Wide Interpretation instead. The Wide Interpretation fits all of his examples seamlessly and seems to be exactly the right translation of the tf–conditional (1) into the language of SQM. But — and here our critique continues — if Vermaas does accept the Wide Interpretation, then his argument for his Inadequacy Claim that SQM violates the Technical Functions Condition collapses, as we shall endeavor to show in the next Section.

We close this Section by noticing that another interpretation of the tf–conditionals (1) is conceivable: another narrow interpretation that replaces 'physical properties' in the Narrow Interpretation with 'physical states', rather than with the disjunction of both as in the Wide Interpretation. However, it will transpire in the next Section that if Vermaas accepts *this* narrow interpretation, then his argument for his Inadequacy Claim also collapses for the same reason as that it collapses whenever the Wide Interpretation is accepted.

4 The Teleportation Scheme

We need not repeat all the details of the teleportation scheme that Vermaas employs in his argument for his Inadequacy Claim that SQM does not satisfy the Technical Functions Condition. We only need to call attention to the fact that Vermaas provides *two* descriptions of the various subfunctions that compose the technical function ϕ_θ of the teleportation apparatus θ with its tf–conditional (4); we call them (i) the *Mixed Description* and (ii) the *Pure Description.* The Mixed Description is a mixture of classically and quantum-mechanically described subfunctions (of a decoder D, a channel C, an encoder E and particles P), wherein the decoder D is treated as a piece of measurement apparatus and the channel C is not treated quantum-mechanically. The Pure Description is a fully quantum-mechanical description of all subfunctions (of decoder D, etc.), wherein the decoder D is not treated as a piece of measurement apparatus and the channel C is treated quantum-mechanically.

The Mixed Description presents no problems for SQM, but the Pure Description does present a problem — or so Vermaas [2005, p. 650] contends. He describes the tf-conditional of the decoder and locates the trouble here, i.e., in conditional (3) of Vermaas (*ibid.*), which we have reproduced in (6). However, as Vermaas argues, the component in the teleportation schema that causes trouble is *not the decoder* but *the channel.* Yet Vermaas nowhere displays the crucial tf–conditional of the channel. In fact, the alleged problematic tf-conditional (6) seems to be a combination of the tf-conditional of the decoder D and of the one of the channel C. In terms of the 'steps' that Vermaas uses in the Pure Description in his Appendix (Vermaas [2005, pp. 657–8]), tf-conditional (6) comprises his steps 1–3.

For the sake of clarity, we distinguish the tf-conditionals of the decoder D and of the channel C, but will only display the ones associated with the alleged problematic channel-function: in (i) the Mixed Description and in (ii) the Pure Description.

(i) In the Mixed Description, the function of the channel is:

To transmit a classical signal from decoder to encoder. (7)

The concomitant tf–conditional (1) of the channel is:

$$\text{classical signal } s_j \text{ enters } C \quad \Box\!\!\rightarrow \quad \text{classical signal } s_j \text{ leaves } C. \tag{8}$$

To repeat, this tf–conditional (8) of the channel in the Mixed Description poses no problem for SQM, as Vermaas [2005, p. 650] emphasises. However, according to Vermaas SQM cannot 'reproduce' the tf–conditional of channel C when translated into the Pure Description, because channel C turns out to be in a physical state that is an improper mixture. The standard property postulate of SQM then prohibits the ascription of the relevant physical properties required by this tf–conditional. (We observe parenthetically that Vermaas interprets physical result $\mathcal{R}_j$ and physical circumstance $\mathcal{C}_j$, as they occur in the formulation of Technical Functions Conditions, *as physical properties*, otherwise it would have been impossible to consider the possibility of SQM to satisfy or to dissatisfy the relevant tf–conditionals.)

(ii) In the Pure Description, however, we obtain a completely different channel-function and associated tf–conditional than the one of (8). Actually, *so does Vermaas*, although not when discussing the alleged Pure Description of the decoder — which results in his tf–conditional (3) (*ibid.*) —, but when presenting the complete Pure Description of the teleportation schema in the Appendix. In this Pure Description, the channel-function (step 2 to step 4 in the Appendix of Vermaas [2005, pp. 657–8]) is to guarantee that the state of the composite physical system of the three particles, decoder D, channel C and encoder E evolves to the state in formula (11) of Vermaas (*ibid.*), after which step 4 of the experiment is conducted, as displayed in Vermaas his formula (12) (*ibid.*). The concomitant tf–functional (1) of channel C in the Pure Description is thus:

$$\text{quantum state } W_2 \text{ enters } C \quad \Box\!\!\rightarrow \quad \text{quantum state } W_5 \text{ leaves } C\ , \tag{9}$$

where W_2 and W_5 are the states after step 1 and step 4 respectively, of which the explicit forms need not detain us. The phrases ‘enters C’ and ‘leaves C’ must now be understood as the channel C transforming the initial, ‘incoming’ state W_2 of the composite system into the final, ‘outgoing’ state W_5 of the composite system. In the literature on quantum information theory (which proceeds wholly within the confines of SQM), such a state transformation is generic and called a *quantum operation*, defined as a completely positive and trace non-increasing mapping on the state-space (of the composite system in the case at hand); cf. Nielsen & Chuang [2000, p. 356]. Thus SQM can easily accommodate the tf–conditional (9) of the channel in the Pure Description and thus we see that neither the channel C itself, nor its functioning in relation to the decoder D give rise to any trouble for SQM.

In fact, all subfunctions of the different components of the teleportation apparatus can best be seen as state transformations in the Pure Description and hence as quantum operations. In his Appendix, Vermaas describes the teleportation process completely in this fashion; all of his steps 1–5 that constitute the teleportation process *are* state transformations and hence quantum operations; cf. Vermaas [2005, pp. 657–8]. Thus in both antecedent and consequent of the tf–conditionals (1) associated to the subfunctions (or 'steps'), one needs to ascribe states — pure and mixed — and not properties. This requires the Wide Interpretation of the tf–conditional (1) in the Technical Functions Condition, and rules out the Narrow one. But then again, as soon as the Wide Interpretation is adopted, which is the one that Vermaas effectively adopts — and must adopt in order to describe his technical artefacts properly —, SQM no longer violates the Technical Functions Condition, because, to repeat, SQM 'reproduces' such Widely interpreted tf–conditionals straightforwardly. Vermaas his argument for his Inadequacy Claim collapses. (One easily verifies that his argument also collapses when adopting the other narrow interpretation, rather than the Wide one, which mentions physical states only and was briefly mentioned in the last paragraph of the previous Section.)

5 Conclusions

Our conclusion is that thus far technological adequacy, in particular the Technical Functions Condition, has failed to be an interpretation-condition that brings us closer to a solution of the selection-problem.

Is there, then, perhaps *another* interpretation of quantum mechanics, besides SQM, that violates the Technical Functions Condition when the tf–conditionals (1) are interpreted Widely? Not as far as we can see. Vermaas [2005, p. 660] briefly discusses two members of the family of modal interpretations of quantum mechanics, namely the spectral and the one that selects a preferred physical magnitude, and argues that the spectral modal interpretation violates the Technical Functions Condition whereas the one choosing a preferred magnitude meets it, *provided* the preferred magnitude just happens to be the signal-magnitude of the channel C in a teleportation device. But this argument too relies on the Narrow Interpretation of the tf–conditional (1) of the Technical Functions Condition. As soon as the Wide Interpretation is adopted, both modal interpretations fare well. This reinforces our conclusion of the previous paragraph: thus far technological adequacy fails to be an interpretation-condition that brings us closer to a solution of the selection-problem. Whether some *other* interpretation-condition from the realm of technology can be found that will bring us closer, only the future can tell.

Finally, what if Vermaas does *not* reject his Narrow Interpretation so as to have an argument for his Inadequacy Claim? Well, then every single piece of measurement, preparation, decoding, encoding and teleportation apparatus, all of which require technical functions that essentially involve the ascription of physical states rather than of physical properties, does no longer qualify as a technical artefact. His argument with the teleportation scheme then cannot even take off. On top of that: these physical systems indisputably *are* technical artefacts. Vermaas can only adopt the Narrow Interpretation on pain of contradiction.

In summary, to adopt the Narrow Interpretation of the tf–conditionals (1) in the condition of technological adequacy yields contradictions, and to adopt the Wide Interpretation of tf–conditionals does not yield any progress in solving the selection-problem. To repeat, whether the notion of technological adequacy can be extended so as to yield an interpretation-condition that will yield any progress in this regard, only the future can tell. If, some day, there were to arrive some condition from the realm of technology that does away *uno icto* with all sorts of strange interpretations of quantum mechanics — many worlds, many minds, bare theory —, then we hereby promise to receive it with a standing ovation.

Acknowledgments

We thank two anonymous Referees for remarks.

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