A Philosopher Looks at Quantum Information Theory*

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Recent suggestions to supply quantum mechanics (QM) with realistic foundations by reformulating it in light of quantum information theory (QIT) are examined and are found wanting by pointing to a basic conceptual problem that QIT itself ignores, namely, the measurement problem. Since one cannot ignore the measurement problem and at the same time pretend to be a realist, as they stand, the suggestions to reformulate QM in light of QIT are nothing but instrumentalism in disguise.

1. Introduction. The last century ended with the rise of the new and fascinating science of quantum information theory (QIT) which has developed from a visionary idea into a lively and fashionable domain of research, combining physics, computer science, and information theory. The results have been more than promising: physicists have succeeded in harnessing the special features of the sub-atomic world to devise fast algorithms, to decipher unbreakable codes, and to "teleport" quantum states.[1] The success of the theory has been such that lately Christopher Fuchs, one of the rising stars of this new field, has suggested reformulating the conceptual foundations of quantum mechanics (QM) in purely information-theoretic terms (Fuchs 2001a, 2001b, 2002a, 2002b). Fuchs believes that such reformulation gives us better understanding of the

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[1] For an accessible textbook on QIT see Nielsen and Chuang 2000.

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quantum world than any of those that have emerged after so many conferences and debates on the interpretation of QM.

Fuchs is motivated by a view shared by many practicing physicists today that QM needs no interpretation (Fuchs and Peres 2000, 70–71). QIT is thus an opportunity for him to reformulate the foundations of QM in purely pragmatic, or instrumental, terms which are devoid of "self referential paradoxes" and metaphysical obscurities.

Fuchs' suggestion is interesting and challenging, and yet it epitomizes a dominant trend among physicists to dismiss decades of discussions on the foundations and interpretation of QM. At stake here is the old and simple question of what our theories are *about*. Fuchs believes that the way the world *is* constrains what can be known about it and that these epistemological constraints warrant viewing QM in part as a theory about information; hence nothing better than QIT is appropriate to supply foundations for it. Though I am sympathetic to Fuchs' observation about the relation between ontology and epistemology in QM, I argue that nevertheless QM—indeed scientific theories in general—are about the world around us, and so interpretational questions are part and parcel of the scientific enterprise. This paper is thus aimed to rehabilitate and defend the conceptual foundations of QM in light of the development of QIT.

There are many ways one can object to the reconstruction of the foundations of QM on the basis of QIT. First, one can approach the issue from a methodological perspective. For example, if one is motivated by the idea that theoretical concepts should not be invented only for pragmatic purposes but to understand what is really going on, then one can claim that the interpretative "flow of information" between QM and QIT should be from the former to the latter and not vice versa. Second, one can elaborate on an old philosophical aphorism and say that pragmatism in science—the idea that the scientific method, as far as it is a method, "is nothing more than doing one's damnedest with one's mind, no holds barred" (Bridgman 1945)—is perfectly fine if you are an engineer, whose income depends on constructing machines that work, but is rather more like junk food if you are a philosopher whose livelihood depends on analyzing conceptual difficulties.

I am afraid, however, that both forms of defence—no matter how plausible—are bound to convince no one but the already converted. My strategy is thus not to defend but to attack. After all, if engineers usually solve well-defined problems, then philosophers usually find problems in what previously were thought well-settled solutions. My argument is simple. Fuchs offers us what he calls a new basis for the foundations of QM while *denying* that in so doing he adopts instrumentalism. And yet this new basis is infected with the very problem that interpretations of QM originally set out to resolve, namely, the quantum measurement problem. This situation in itself is harmless if one simply *ignores* the problem; yet ignoring the problem is tantamount to admitting instrumentalism. Thus Fuchs' dilemma is as follows: either he is a realist, but has not solved the measurement problem (which is fatal for the project) or he is not. In both cases Fuchs' original proposal is simply inconsistent.

The rest of the paper is organized as follows. In Section 2 I present Fuchs' suggestion to reformulate the foundations of QM in light of the developments in QIT. In Section 3 I show how QIT ignores the measurement problem. Section 4 demonstrates how this problem can be solved within the foundations of QM itself. The conclusion is spelled out in Section 5.

2. Are There no Sundays in a Quantum Engineer's Life? QM is infamous for its measurement problem, i.e., the problem that any attempt to account with the quantum formalism for the simple fact that measurements have results requires an arbitrary "shifty split" between the classical and the quantum world. At the heart of the measurement problem lies the mutual inconsistency of the three following claims: (1) The wave function of a system is complete; the wave function specifies *all* the physical properties of a system; (2) the wave function *always* evolves in accord with a linear dynamical equation (the Schrödinger equation); (3) measurements of, e.g., the spin of an electron, always (or at least usually) have determinate outcomes, i.e., at the end of the measurement the measuring device is either in a state which indicates spin up (and not down) or spin down (and not up).

The founding fathers, Dirac and von-Neumann, insisted on (1) and (3), and so they had to reject (2) and to postulate a collapse of the wave function due to the measurement. It was claimed that after the measurement the superposition captured by the wave function "shrinks" to one of the eigenvalues of the eigenstate of the observable measured. As John Bell (1990, 35) notes, the orthodox collapse postulate involves *two* quantum jumps, one of the classical apparatus to the eigenstate of its 'reading' and one of the system to the eigenvalue of that eigenstate.

But the orthodox view is widely held to be unsatisfactory. In Bell's own words:

> It would seem that the theory is exclusively concerned about 'results of measurements' and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of the "measurer"? Was the wave function of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better-qualified system—with a Ph.D.? (Bell 1990, 34)

Bell's (1987, 201) insight was that in order to solve the measurement problem one must either admit that the wave function is not everything (and reject (1)) or admit that Schrödinger's equation is not always right (and reject (2)). In other words, in order to solve the measurement problem either the kinematics of orthodox QM or its dynamics must be modified. The first alternative leads to Bohmian mechanics and to modal interpretations;[2] the second, to spontaneous localization theories, e.g., GRW or CSL (Ghirardi et al. 1986; Pearle 1997). Agreed, one can always reject (3) but then one must supply an explanation how measurements *appear* to have definite results although they actually do not. This alternative leads to Everettian theories, also known as many-worlds interpretations.[3]

Of course, this way of classifying the possible solutions to the measurement problem is not unique. Clifton and Bub, for example, have proved a uniqueness theorem for no-collapse interpretations with which one can distinguish further between no-collapse theories according to what counts as a "beable," or as an observable with a definite value, in each theory (Bub 1997, chap. 4)[4]. Presented as they are here, however, the possible solutions to the measurement problem can be easily distinguished according to the way each of them answers the question "what are the quantum probabilities—the probabilities which are calculated according to Born's rule—probabilities for?"[5] Thus, for example, in Bohmian mechanics these probabilities are for particles to have certain configurations, and we understand them similar to the way we understand the probabilities of statistical mechanics. In spontaneous collapse theories these probabilities are for the wave function to evolve in a certain way, and we understand them as purely chancy dynamical transition probabilities. How to understand quantum probabilities in an Everettian context is still an open question. Recent work by Saunders (1998), Deutsch (1999), and Wallace (2002) suggests how to interpret them within a decision-theoretic scheme. In this framework the quantum probabilities are probabilities for rational observers to make decisions with respect to their own 'branching,' and further proofs are given in order to show how the 'weights' on each branch are equal to the probabilities given by Born's rule.

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[2] For an accessible exposition of Bohmian mechanics see Albert 1992, chap. 7. Further technical details are found in Goldstein et al. 1992 and in Holland 1993. Modal interpretations are presented in van Fraassen 1991, chap. 9. See also Bacciagaluppi and Dickson 1999.

[3] For a classification of this type of theories see, e.g., Wallace 2002, 1–2.

[4] Interestingly, when matters are put in these terms the instrumentalism of the Copenhagen interpretation in which the "beable" varies with the experimental set-up becomes even more evident.

[5] For a lucid presentation of this idea see Maudlin 2001, 283–285.

And yet, a dominant attitude among physicists is to ignore the measurement problem, arguing, as Fuchs and Peres (2000) do, that "quantum theory needs no interpretation." Physicists say that they use quantum mechanics to calculate probabilities for results of experiments and that the theory does not describe matters of fact in the world but rather provides an algorithm for computing these probabilities. The probabilities of QM are simply probabilities for *finding* the system in a certain state, and physicists leave the 'philosophizing' to philosophers or to "physicists who have lost their taste or ability for 'real' physics." (Unruh 1986, 242). John Bell was an example of the contrary, recognizing that although it was difficult to point at any real discovery that arose out of concerns having to do with quantum measurement theory in his time, denying its significance amounted to denying the main reason why many physicists were what they were, namely, the desire to understand the world. "I am a quantum engineer," he said, "but on Sundays I have principles."[6]

The decade since Bell's death has seen much progress in the foundations of quantum mechanics. Conceptually improved alternatives to orthodox QM were formalized and a better understanding of the disagreements was achieved. But this decade has also seen the birth of the new science of QIT. Suddenly quantum weirdness has become a resource for engineers and the scientific focus has shifted from understanding this weirdness to harnessing it.

One could think that with the rise of QIT the neglected measurement problem would once again attract physicists' attention, and that with the improvement of technology and the possibility of creating macroscopic superpositions metaphysics would become experimental again.[7] Unfortunately, the physics community has chosen otherwise.

In fact, instead of using QIT to gain better understanding of the interpretation of QM, scientists who found a new playground for QM in the domain of QIT are suggesting now that we *reformulate* the foundations of the former on the basis of the conceptual framework of the latter (see, e. g., Wheeler 1989; Caves et al. 2000; Clifton et al. 2003). The most lucid advocate of this approach is Christopher Fuchs, who presents the motivation for his idea in the following way:

> The issue at stake is when will we ever stop burdening the taxpayer with conferences and workshops devoted—explicitly or implicitly—to the quantum foundations? The suspicion is expressed that no end will

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[6] John Bell's opening words in an "underground colloquium," cited in Gisin 2002.

[7] It was Abner Shimony who coined the phrase "experimental metaphysics" in the context of Bell's inequalities and Aspect's experiments.

> be in sight until a means is found to reduce quantum theory to two or three statements of crisp physical (rather than abstract, axiomatic) significance. In this regard, no tool appears to be better calibrated for a direct assault than quantum information theory. Far from being a strained application of the latest fad to a deep-seated problem, this method holds promise precisely because a large part (but not all) of the structure of quantum theory has always concerned information. It is just that the physics community has somehow forgotten this. (Fuchs 2001b, 1).

Fuchs (2002b) begins with an analogy, insinuating that the relation between QIT and the whole class of interpretations of QM is analogous to the relation between Einstein's special theory of relativity (STR) and Lorentz-Fitzgerald contraction theory. He (rightly) claims that the principles Einstein introduced in STR supplied an understanding to the abstract mathematical structure of Lorentz transformations, but then he argues that a similar move is required in QM, i.e., that we should substitute the old axioms of QM with information-theoretic justifications in order to regain better understanding of the abstract structure of Hilbert space.

The motivation for such a radical move, says Fuchs (2001b, 8–9), comes from Einstein, who, given his separability principle, regarded the quantum state as an incomplete description of reality.[8] Einstein, of course, saw the incompleteness of the quantum state as a feature of the theory, and not of the world. Fuchs, however, along with most of physics community, draws opposite conclusions:

> The theory prescribes that no matter how much we know about a quantum system—even if we have *maximal* information about it—there will always be a statistical residue. (2001b, 9)

So far there is nothing new here; quantum "incompleteness" is indeed an existent fact, and no "hidden variables" theory can complete it without violating STR. But Fuchs goes further to declare that the mystery of that existent fact cannot be removed even if we endow the quantum state with an ontological status. Note that Fuchs is making a dangerous generalization here. There is a big difference between Bohmian mechanics, or any other no-collapse interpretation which denies the completeness of QM, and

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[8] Einstein in a letter to Born in Born 1970, 170–171: "An essential aspect of this arrangement of things in physics is that they lay claim, at a certain time, to an existence independent of one another, provided these objects 'are situated in different parts of space.' Unless one makes this kind of assumption about the independence of the existence (of 'being thus') of objects which are far apart from one another in space—which stem in the first place from everyday thinking—physical thinking in the familiar sense would not be possible."

collapse interpretations which accept it; and, it is exactly this difference which we are about to elaborate in what follows.

Fuchs proceeds to convince his reader of the necessity of reconstructing the foundations of QM by referring again to Einstein, this time to the general theory of relativity (GTR). Here the claim is that GTR geometrized nature and detached it from coordinate charts. The idea is that we should do the same in QM, i.e., make clear the distinction between the observer and the observed in order to gain insight about Nature itself. An important difference between the co-ordinate charts in GTR and the observer in QM, however, is that the latter is an active agent, whose impact on Nature is similar to the impact of matter on the geometry of spacetime:

> Observers, scientific agents, a necessary part of reality? No. But do they tend to change things once they are on the scene? Yes. If QM can tell us something truly deep about nature, I think it is this. (Fuchs 2002b, 6f).

Fuchs' analogies are shrewdly (not to say diplomatically) contrived. The first analogy to STR drives home the lesson that the interpretations of QM are nothing but metaphysical flim-flam: just as STR and Lorentz-Fitzgerald theories are empirically indistinguishable, so are QM and its interpretations; and since in the former case the physics community has chosen the less metaphysically extravagant option, we should do the same in the latter. The second analogy to GTR allows Fuchs to acknowledge the existence of an external world independent of an observer but to insist that the ontology of this world is such that it puts constraints on the information-gathering capacities of the observer, i.e., on epistemology. Thus, if the world is contrived in a way that it conceals information from us then the science of this world should be a science about the sort of information we can have and how this information can be moved around, hence QIT.

It is important not to read Fuchs as saying that QM is *only* about knowledge or information since such a reading misses the point. The analogies above make it clear that Fuchs follows the well-known Kantian idea of the relation between epistemology and ontology, but "with a twist." The ontology of the world we live in constrains our epistemology, thus precluding the possibility of knowledge of the world "in itself," independent of an observer. Classical physics is an example of an "observer-free" science in which physical systems are endowed with independent physical properties. If one wants such an "observer-free" description in QM, one ends up with Bohmian mechanics (see Bub 1997). Of course, this theory violates Lorentz invariance, but it also incorporates a mechanism for hiding this violation. In this sense Bohmian mechanics is to QM what Lorentz-Fitzgerald theory is to STR. But if the observer's epistemology is inevitably constrained, i.e., the reality is always "veiled," to borrow d'Espagnat's term, (although not in the conspiratorial Bohmian sense of concealing undetected violations of laws), then from a philosophical point of view, science must capture this feature, which is an *objective* feature of the world. Since "philosophy is too important to be left to the philosophers" (Fuchs (2002b, 7) cites J.A. Wheeler), the foundations of science should be left to the quantum information theorists.

The philosophical tradition behind the idea that the peculiar features of QM cannot be attributed to the "things in themselves" goes back to Berkeley, Kant, and Mach, and many of the founding fathers of the theory accepted it either deliberately or opportunistically. Fuchs, as we have seen, is more sophisticated than that. He takes pains to convince us that his claim is exactly the opposite: the peculiar features of QM are indeed a part of reality, but in order to grasp them crisply one should avoid quantum interpretations and instead strive to justify the original QM axioms all interpretations start with by simple information-theoretic principles.

Fuchs emphasizes throughout his writings that he is neither a Kantian nor an idealist, but despite the diplomatic apologetics, the main thrust of his argument cannot be disguised. Kant was shrewdly silent about the world "in itself" and never gave his critics the joy of catching him in anti-realistic statements. Nevertheless, Kant was no realist, and the picture of man dictating Nature its laws is nothing but (some might say distorted) Kantian legacy. In a similar vein Fuchs says:

> This attempt to be absolutely frank about the subjectivity of *some* of the terms in quantum theory is a part of a larger program to delimit the terms that *can* be interpreted as objective in a fruitful way. (2002b, 7f)

Agreed, that the "surface" terms of QM describe knowledge or information does not automatically entail anti-realism about the world. But the realistic approaches to QM are exactly the ones Fuchs mocks:

> Go to any meeting, and it is like being in a holy city in great tumult. You will find all the religions with all their priests pitted in holy war—the Bohmians, the Consistent Historians, the Transactionalists, the Spontaneous Collapseans, the Einselectionists, the Contextual Objectivists, the outright Everettics, and many more beyond that. They all declare to see the light, the ultimate light. Each tells us that if we will accept their solution as our savior, then we too will see the light. . . . Despite the accusations of incompleteness, nonsensicality, irrelevance, and surreality one often sees one religion making against the other, I see little to no difference in *any* of their canons. They all look equally detached from the world of quantum practice to me. For, though each seems to want a firm reality within the theory—i.e., a single God they

> can point to and declare, "There, that term is what is real in the universe even when there are no physicists about"—none have worked very hard to get out of the Platonic realm of pure mathematics to find it. (2002b, 2–3)

His own rejoinder is to discover the underlying reality by way of rewriting the foundations of QM with QIT. In itself this is an admirable task, yet it is but a Pyrrhic victory if what is left of "objective reality" after such an enterprise is quite "minuscule" (Fuchs' (2002b, 6) own term). Two such terms that can carry objective ontological weight which Fuchs is willing to admit are the quantum *system* and the *dimensionality* of the Hilbert space which accompanies it. Although the *states* of the quantum system represent only "a collection of subjective degrees of belief about *something* to do with that system," the latter "represents something real and independent of us." (Fuchs 2002b, 5)

Motivated in this way Fuchs (2002b, 42–43) then goes on to "trash" (Fuchs' own description of his attempt to understand QM) about as much of QM as he can: he argues that "quantum states—whatever they are—cannot be objective entities"; that "there is nothing sacred about the quantum probability rule and that the best way to think of a quantum state is as a state of belief about what *would* happen if one were to ever approach a standard measurement device locked away in a vault in Paris"; that "even our hallowed quantum entanglement is a secondary and subjective effect"; and that "all a measurement *is* is just an arbitrary application of Bayes' rule—an arbitrary refinement of one's beliefs—along with some account that measurements are invasive interventions into nature." Finally he argues that "even quantum time evolutions are subjective judgements; they just so happen to be conditional judgements."

But what is "real" in QM According to Fuchs?

> If one is looking for something "real" in quantum theory, what more direct tack could one take than to look to its technologies? People may argue about the objective reality of the wave function ad infinitum, but few would argue about the existence of quantum cryptography as a solid prediction of the theory. Why not take that or a similar effect as the grounding for what quantum mechanics is trying to tell us about nature? (Fuchs 2002b, 49)

It turns out that the result of Fuchs' "realistic" enterprise, albeit an enterprise covered with much apologetic sauce, ala Kant, is that the only real property one can endow the world "in itself" is that it is sensitive to our experimental interventions. This was, indeed, Fuchs' only conclusion in a predecessor to the paper discussed here (Fuchs 2001b), yet he himself now admits that this conclusion was "singularly unhelpful to anyone who wanted to pursue the program further" (Fuchs 2002b, 51),[9] and so his humble rejoinder is that what is real "out there" is nothing but the dimension of the Hilbert space associated with the quantum system.[10]

Not surprisingly, if one identifies quantum theory as "law of thought" rather than a law of Nature, as Fuchs does, then less of the content of the theory corresponds to reality. But Fuchs is convinced that the consequence of his project—the admission that Nature is sensitive to our interventions—counts as an achievement that warrants throwing away decades of quantum foundational discussions.

As I have said in the introduction, I shall not try to convince the converted and defend quantum interpretations against Fuchs' rebuttal. Nor shall I argue that Fuchs' "realism" is a caricature. Instead in the next section I shall launch an attack on another central thesis of Fuchs' project.

3. Trouble in Paradise. Fuchs' project of supplying an information-theoretic justification to the axioms of QM by way of rewriting the foundations of QM in terms of QIT leads to realism which is quite "thin." Thus, although Fuchs is at pains to make it clear he is not a full-fledged anti-realist, the outcome of his efforts speaks for itself. Nevertheless, since there is no point in getting into a debate about what reality *is,* I shall abandon this line of defence, and move to a different, more active, one.

In this section we are about to discover that no matter how Fuchs makes fun of the quantum measurement problem[11]—the core foundational problem of QM—the problem continues to haunt him even in QIT. As a result, Fuchs' own characterization of his project in realist terms becomes suspect.

The argument is simple. Fuchs offers us what he calls a new basis for the foundations of QM while *denying* that in so doing he adopts anti-realism. And yet this new basis is infected with the very problem the interpretations of QM have originally set forth to resolve, namely, the quantum measurement problem. This situation in itself is harmless if one simply

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[9] The similarity to Kant's apologetics is striking. As mentioned before, Kant was reluctant to attribute any property or structure whatsoever to the "thing in itself," and yet, Kant's solution to the third antinomy signifies a rare moment in his philosophy, i.e., his awareness of the dire consequences of this reluctance. It is also one of the exceptional places in Kant's philosophy where he does assign some property, e.g., freedom, to "the unconditioned condition," if only to save the human race from the doom of life without morality.

[10] The dimension of the Hilbert space associated with a quantum system appears to be a crucial physical resource in deciding whether a quantum computer can be physically realized in a way that will ensure tractability of its computations. See Caves et al. 2002a.

[11] As Fuchs (2002b, 13) puts it: "Hideo Mabuchi [another practicing physicist] once told me, 'The quantum measurement problem refers to a set of people.' And though that is a bit harsh, maybe it also contains a bit of the truth."

ignores the problem; but ignoring the problem is tantamount to admitting anti-realism. Thus Fuchs' dilemma is as follows: either he is a realist, but has not solved the measurement problem (which is fatal for his project) or he is not. Both outcomes are inconsistent with Fuchs' original proposal.

3.1. The Quantum State—It or Bit? One's attitude towards the quantum measurement problem depends on the way one treats the wave function. If no interpretation is needed, as some physicists say, then one can adopt an *epistemic* attitude in which the wave function simply supplies statistical information for measurement results. The probabilities computed by the standard Born rule are then probabilities of *finding* the system in a specific state. Collapsing the wave function, under this account, is just an adjustment of subjective probabilities, conditionalizing on newly discovered results of measurement. No physical change takes place since the wave function represents only what we *know* about the system. If quantum states merely represent points of view of observers, then there is no genuine measurement problem. The change in the quantum state as a result of a measurement, dictated by the orthodox collapse postulate, is only a change in the observer's knowledge, or probability assignments, whereas the Schrödinger equation describes the time evolution of these probabilities when no measurement takes place.

The idea that the quantum state represents information of an observer is a legacy of the "Copenhagen school." It is also epitomized in Wheeler's idea of the *participatory universe:*

> It from bit symbolizes the idea that every item of the physical world has at the bottom—at the very deep bottom, in most instances—an immaterial source and explanation; that which we call reality arises in the last analysis from the posing of yes-no questions and the registration of equipment-evoked responses; in short, that all things physical are information-theoretic in origin and this is a *participatory universe*. (Wheeler 1989, 5)

This epistemic view of the wave function is also central to Fuchs' program, and yet he insists that the latter should not be interpreted as mere idealism or instrumentalism:

> The point is that deep within quantum theory we hope to find an ontological statement. But that direct ontological statement will refer to our interface with the world: the world is wired in such an such a way that surface terms of the theory (the density operators) can only refer to our subjective state of knowledge. That does not negate that there is a world out there and that we strive to say useful things about it. (Fuchs 2001a, 99)

We have seen that the amount of useful things Fuchs' allows himself to say about the world "out there" is "minuscule"—an understatement in light of the consequence of his reformulation. But in what follows I want to focus on another central idea of Fuchs' project, i.e., the idea that one can maintain an epistemic view of the wave function and still declare oneself non instrumentalist, or a realist of some sort. The claim I make here is that the epistemic view can be rendered consistent only in the price of denying even the weakest form of realism Fuchs alludes to.

3.2. The Story About Adam and Eve. In an attempt to demonstrate that quantum mechanics does need an interpretation, Meir Hemmo (unpublished) offers the following set up.[12] Consider an experiment done in a lab, and two separated observers, Eve—confined to the lab; and Adam—outside the lab. Say that Eve is about to measure a spin 1/2 electron in some direction. QM tells Eve what are the probabilities for the two possible results. When Eve performs the experiment her measuring device gets entangled with the electron to yield a superposition that cannot be taken to describe a single result of the measurement, and as a result the pure quantum algorithm stands in flat contradiction to the empirical fact that measurements have (or appear to have) results. Indeed, this is no more than the quantum measurement problem re-construed.

Now if one takes an epistemic stance toward the wave function, one can evade this problem by suggesting that the latter simply provides mathematical short hand for information or knowledge available to an observer, in order to compute probabilities for results of experiments. Thus, the tension between the unitary Schrödinger evolution and the single determinate result to be accounted for is relieved as long as one assumes that quantum states which are encoded in the wave function are relative to the information available to the observer, that is, that quantum states depend on the knowledge of the observer and that these states of knowledge are updated simply by applying the orthodox collapse postulate, which in this case has no factual meaning. On this picture, after the experiment has been performed, Eve updates her knowledge with one of the two possible outcomes by applying the collapse postulate and replacing the superposition with a state corresponding to the result obtained.

We now move outside the lab to consider the point of view of Adam. Here we notice that Adam's knowledge of the quantum state of the entire lab remained the same superposed state that was available to Eve before she updated her knowledge. Now if Adam wishes to compute the state of the lab after Eve's measurement, he can do so with Eve's *reduced* state,

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[12] This set up is a variant of a thought experiment that was originally proposed by Wigner and is commonly known as "Wigner's friend".

that is, the state confined to the observables of Eve alone, by tracing over all the degrees of freedom other than the relevant ones of Eve. But since no factual collapse ever occurred in the lab, this reduced state cannot be considered to be a classical mixture; it must be an improper mixture.[13]

The epistemic view thus leads to a situation in which the same state is described differently by two observers. From the point of view of Eve the state is pure. From the point of view of Adam the state is an (improper) mixture. Agreed, the two descriptions cannot be distinguished and infinitely many experiments will yield matching subsequent computations. Moreover, it can be shown that no measurement of observables pertaining to the lab alone (i.e., to Eve, to her measuring apparatus, or to the electron) can decide between them. The reason for this is that the probability distribution for such measurements is completely fixed by the reduced states of the relevant systems.[14]

And yet, QM itself tells us that there *are* experiments that can distinguish between the two descriptions.[15] Indeed, if no super-selections rules are imposed, then there exists an observable of the lab for which the entangled state of the electron and the measuring apparatus and Eve's mind (or the part of it that records the outcome) is an eigenstate with some definite eigenvalue, and for which the "collapsed" state after the measurement is *not* an eigenstate (since the superposition and one of its components are *not* orthogonal). For these special observables, if Eve and Adam compute the probabilities for subsequent measurements to be carried out at some time on the basis of the information that is available to them *now,* they will inevitably come up with *different* predictions: Adam's prediction will be determined by the definite eigenvalue of the observable, while Eve's prediction will be probabilistic since for her the state in the lab is not an eigenstate of the observable. Hemmo concludes that this indicates that the epistemic view is inconsistent, since it yields two different predictions for one and the same experiment, no matter how complicated and difficult the actual performance of the experiment will be.

3.3. What Price Consistency? If one is a sophisticated proponent of the epistemic view, then one has at least two ways to oppose Hemmo's argument. The point I wish to make, however, is that in so doing one automatically characterizes oneself as an instrumentalist, and this flatly contradicts Fuchs' original claim to supply QM with realistic foundations.

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[13] On the difference between the two see, e.g., d'Espagnat 1966.

[14] The first to point at this feature of quantum composite systems is Furry 1936.

[15] This idea goes back to Albert's (1983; 1990) "self measurement." See also Bub 1997, 207–212.

The first objection one can raise in order to defend the consistency of the epistemic view in light of Hemmo's *thought* experiment is exactly that the latter is a thought experiment, and that for all practical purposes (FAPP) such re-interference experiments are impossible. The basic idea behind this FAPP objection is that it is practically impossible to isolate physical systems and hence due to environmental decoherence no such re-interference experiments can actually be performed: the superposition in the lab, which is the source of the alleged inconsistency, will rapidly decohere.

More precisely, if we assume that decoherence conditions hold, i.e., that the interaction Hamiltonian between the environment and the lab commutes with the pointer observables of the lab in the position basis, and that the Hilbert spaces of the lab and the environment form a tensor product at the beginning of the interaction, then the state in the lab (including Eve's mind) would rapidly get entangled with the environment and the original interference operator would become the *wrong* operator to measure.[16] As a result not only can we never distinguish *in the lab* between a collapsed state and a *reduced* state, the latter being one in which interference terms are delocalized into the environment, but also, since the recoherence time scales are larger than the age of the universe, for all practical purposes the state will never recohere.

And yet, decoherence by itself cannot and does not solve the measurement problem in the way that collapse interpretations, no collapse interpretations, or hidden variables theories, do. What it can do is to supply a consistency proof for the *appearance* of a classical world with an underlying quantum dynamics. It can explain why we never see macroscopic superpositions, not why they do not exist. Relying on decoherence alone, the epistemic view renders QM a theory that can never be caught in a lie rather than a theory that tells the truth. No realist can deny there is a difference here.[17]

The second objection that a proponent of the epistemic view can raise hinges on the time-reversal-invariant character of orthodox QM.[18] Let us call it the Erasure objection. One might claim that even if interference experiments could be performed, then they would "erase" Eve's memory since Adam—having as he does complete control of all the degrees of

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[16] A clear illustration of this situation is given in Barret 1999, chap. 8.

[17] One can use decoherence to secure an *effective* state in the lab, but since this path leads to no-collapse *interpretations*, following it is tantamount to surrendering the "no interpretation" thesis which underlies the epistemic view of the wave function.

[18] Here I adopt the common view that the dynamics in QM are invariant under temporal reflection *and* complex conjugation, that is, $\psi(x,t)$ is a solution of Schrödinger's equation if and only if $\psi^*(x,-t)$ is, for all ψ.

freedom in the lab—could undo Eve's observation. In other words, since according to the epistemic view the collapse is non factual, Schrödinger's equation allows such reversal; and since Eve's memory and the interference observable do not commute, Eve will have no record whatsoever of her "collapsed" state and consistency would be restored.

Hemmo's response to the Erasure objection is to press on. The epistemic view, he says, cannot escape contradiction since there must be *a fact of the matter* whether a result of an experiment is deterministic or probabilistic, irrespective of one's knowledge of it.

Note, however, that this response presupposes a certain realistic stance towards quantum probabilities. In saying that "there must be *a fact of the matter* whether a result of an experiment is deterministic or probabilistic" Hemmo clearly regards quantum probabilities as objective propensities, which is exactly what Fuchs takes great pains to deny. According to the epistemic view, quantum probabilities are not objective propensities. Rather, they are degrees of subjective belief, or gambling commitments, and as such can co-vary with different observers, as long as the state-assignments of the two observers are compatible, i.e., as long as the state-assignments do not differ in an arbitrary way.[19]

Thus, a better response than Hemmo's to the Erasure objection which does not attribute to the epistemic view an assumption it denies would be to show that Adam's and Eve's state-assignments are *incompatible*. It turns out that according to one compatibility condition this is indeed the case;[20] but according to another it isn't.[21] It seems that the discussion threatens to be degraded to mere book-keeping, so let me quickly point out again that the issue at stake is not whether the epistemic view is consistent, but what price its consistency.[22]

As in the case of the FAPP objection, the epistemic view reclaims consistency only at the price of instrumentalism, since relativizing quantum probabilities to the observer (which is analogous to what Einstein did to

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[19] On compatibility conditions for state-assignments see Caves et al. 2002b and Brun 2002.

[20] One such condition which appears in Caves et al. 2002b and goes back to Peierls 1991 is that both state-assignments (1) must be non orthogonal and (2) must commute. In Hemmo's thought experiments condition (2) is violated.

[21] Brun 2002 strengthens Peierls' condition in order to subsume the case where the two observers start with different information which is exactly the case Hemmo's thought experiment describes.

[22] Note that nothing in the formalism of QM prevents us from viewing Adam and Eve as the *same* system (with different degrees of freedom), and so notwithstanding the compatibility of the state assignments, there is still no subjective consistent account of QM probabilities which will explain *all* the statistics of actual experiments.

simultaneity in the special theory of relativity) is tantamount to stipulating an arbitrary cut between the observer and Nature. And although it is true that one can shift this cut according to whim, it is also true that according to the epistemic view what counts as real, i.e., as having definite properties, is now *dependent* on where this cut is made.

Taking stock, one can still argue that Hemmo's thought experiment might not give sophisticated proponents of the epistemic view such as Fuchs much pause for thought. However, it does expose the fact that this view is indifferent to the measurement problem. Since ignoring this problem is tantamount to admitting instrumentalism, while the indifference of the epistemic view to the measurement problem is in itself harmless, it is quite at odds with Fuchs' original goal to supply QM with realistic foundations.

Let me restate the reasons for this inconsistency. First, if in defending the epistemic view against Hemmo's attack one invokes practical experimental capacities (the FAPP objection), then one must also accept that human capabilities dictate Nature's laws. In the eyes of the realist this is a complete misunderstanding of the role of experiments. Experiments are no more than a tool in the hand of science whose aim is to understand the world around us (Bell 1990, 34), and although they are the highest court of appeal for establishing the laws of nature, this does not mean that the *letters* of any law of Nature depend on them. As Planck notes:

> The limitation to the law, if any, must lie in the same province as its essential idea, in observed Nature, and not in the observer. That man's experience is called upon in the deduction of the law is of no consequence; for that is, in fact, our only way of arriving at knowledge of a natural law. But the law once discovered must receive recognition of its independence, at least in so far as Natural Law can be said to exist independent of Mind. (Planck 1945, 106)

Physicists like Mach or Heisenberg could say that the last remark by Planck is exactly the issue at stake and that the existence of natural law independent of one's mind is quite limited in its extent. A devoted realist such as Fuchs would surely deny their claim.

Second, by interpreting quantum probabilities as degrees of belief (the Erasure objection) one subordinates one's ontology to one's epistemology. But while realists can accept that ontology constrains epistemology, they also believe that the former is *independent* of the latter! Consequently, it is difficult to understand how Fuchs can view himself a realist and yet ignore the measurement problem.

3.4. Intermezzo. The upshot of the discussion so far is this. One can grant Fuchs that QM indicates that the ontology of the world puts constraints on our epistemology (call this conjunct (1)) and as a result one must reject no-collapse theories such as Bohmian mechanics or modal interpretations which aim to complete the quantum description. One can also grant Fuchs the epistemic view of the wave function (call this conjunct (2)). But as the objections to Hemmo's thought experiment demonstrate, one must accept that the conjunction of these two ideas is tantamount to saying that epistemology dictates ontology. The latter, of course, is not a position a realist can adopt; hence Fuchs' apologetics and denial of the accusations regarding his "Kantianism," "idealism," and "instrumentalism" turn out to be nothing but window-dressing.

Fuchs, along with many others,[23] seems to think that any realistic approach to QM which says more about the world "in itself" than he allows himself to say, must acknowledge pre-existing reality, i.e., must resurrect a "hidden variables" scheme, and hence is unwarranted:

> . . . Information about what? . . . That information cannot be about pre-existing reality (a hidden variable) unless we are willing to renege on our reason for rejecting the quantum state's objective reality in the first place. (Fuchs 2002, 24)

As noted in Section 2, this generalization does not do justice to the current state of affairs in the foundations of QM. So far the interpretations that follow in some sense Einstein's desiderata and acknowledge pre-existing reality are hidden variables theories such as Bohmian mechanics and modal interpretations. But there are other interpretations in which the quantum state has ontological weight and these are nowhere close to claiming that the statistical character of the theory is not a feature of the world, or that it should be eliminated.

Simply put, Fuchs seems to believe that the only way to resist Einstein's idea of pre-existing reality is to hold to the conjunction of (1) and (2). What Fuchs fails to appreciate, however, is that one can accept conjunct (1)—that ontology constrains epistemology—and still deny conjunct (2), i.e., reject the epistemic view of the wave function, *without* admitting a "hidden variables" scheme. In other words, one can be realistic about QM *and* still hold that the wave function is complete yet supplies only statistical information, and that there is nothing more to be known about the world than is captured in the quantum state. In fact, this is exactly what a certain *collapse* interpretation of QM amounts to.

4. Interpretations—the Forbidden Fruit. Quantum mechanics is undoubtedly weird. The question is what are we going to do about this weirdness. One easy way is to forget the attempts to understand what the theory

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[23] Apart from his influence on the physics community Fuchs has already succeeded in converting philosophers such as J. Bub (personal communication).

says and to harness its weirdness in order to construct sophisticated machinery. There is nothing wrong in such an engineering endeavour. To claim that QM weirdness can be *explained* in terms of this endeavour is, however, something completely different. To claim further that one can maintain that the engineering endeavour has an explanatory role—or even that it is the *only* explanation needed—and to pose as a realist is simply inconsistent.

I can understand how one might argue that any theory that admits quantum information theoretic constraints, such the impossibility of superluminal information transfer between systems by measuring one of them, the impossibility of (perfectly) cloning the information contained in an unknown physical state, and the impossibility of (unconditionally secure) bit commitment, is "quantum mechanical" as far as the characterization of its observables and state space are concerned (Clifton et al. 2003). But this simply means that underlying both QM and QIT is a property structure with a non Boolean character which leads to interference and entanglement. The problem of making sense of this non Boolean character in light of the apparent Boolean character of the property structure that underlies the macroscopic world (which *lacks* interference and entanglement) remains to be solved.

Fuchs' (2002b, 28–39) "solution" is to regard the transition from pure states to mixtures, represented by "the collapse of the wave function," as a variant of Bayes' rule for updating the subjective probabilities of the observer as a *result* of a measurement. This is a "law of thought" that stands over and above the details of physics. But the transition from pure states to mixtures is not the *explanans*; it is the *explanandum*!

QM, a-la Fuchs, is mute about the physical transition from pure states to mixtures since the theory does not describe states of affairs in the world; it describes only our knowledge of them. The "collapse postulate" is thus an adjustment of subjective probabilities in which no physical change takes place. But here again one wonders what does Fuchs mean by denying he is an instrumentalist, if, according to him, our best theory says nothing about this feature of the world (apart, maybe, from that quantum mechanical systems exist and that these systems are "sensitive to our touch"). This attitude is understandable in metaphysics, when one has no fixed background of knowledge to rely on, but here we are dealing with a fundamental *physical* theory, one which is empirically confirmed to a very high degree. To say that this theory is silent about the world and to subscribe to a realist position about this world are two things that simply do not go together.

4.1. Towards a (Macro)realistic QM. Fuchs' oversight is simple. Taking as he does the epistemic stance with respect to the quantum state, i.e., seeing it as a useful epistemic construct for computing conditonalized probabilities, he postulates an arbitrary "split" between the observed and the observer: any attempt to apply the quantum formalism to the measurement process itself will unavoidably lead to further conditional predictions. He further assumes that by eliminating this "split" one admits pre-existing reality and thus is bound to end up with hidden variables theories.

However, one can still accept the "split" between the observer and the observed and yet eliminate its arbitrariness *without* postulating hidden variables. In so doing one is led to a realistic interpretation of the quantum state that, contrary to Fuchs' assumption, views the quantum formalism as complete but also *incorrect*. In this realistic interpretation, the spontaneous localization scheme (SL), the collapse of the wave function is a physical process; a natural consequence of the dynamics. Since a lot of ink has been spilled on this interpretation (the interpretation that goes back to Ghirardi et al. 1986), what I would like to emphasize here, in light of Fuchs' oversight, is only the differences between this approach and the view that regards the quantum formalism as *incomplete*—the view that Einstein was referring to when he presented his EPR argument.

Hidden variables theories regard the quantum formalism as incomplete. The quantum probabilities in these theories are epistemic probabilities that signify our lack of knowledge, or ignorance, of the exact state the system *is* in. Realism in this sense is better understood as applying to the objective definiteness of the quantum state, and the statistical character of the theory is due to the incompleteness of the formalism and not to any intrinsic quantum indefiniteness. In Fuchs' terminology, the quantum state supplies in this case incomplete information on pre-existing reality.

In contrast, the SL approach regards the quantum formalism complete. But it also modifies this formalism and in this respect it is better understood as a replacement—not as an interpretation—of contemporary QM.[24] The quantum probabilities, according to this approach, are objective, i.e., they signify pure chance. The question is then what is so realistic about this theory? The answer is threefold: the theory is realistic about (1) the wave function, (2) its collapse, and (3) the quantum "weirdness," i.e., non separability. In the non-relativistic versions of the SL approach the physical state of an isolated system at time t is described with its wave function.[25] Everything else, e.g., particles and their positions in 3D space, supervenes

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[24] Note, moreover, that since the predictions of the SL theory *differ* from those of QM, there exists in principle a way to *distinguish* between the two. Thus, following Gisin 2002, I find the FAPP objection rather curious: there is nothing to be proud of when one cannot be proved wrong, since this also means that (in a scientific relevant way) one cannot be proved right!

[25] The issue whether a Lorentz invariant collapse theory is possible is beyond the scope of this paper. See, e.g., Bell 1987, 206–208; Albert 2000; Myrvold 2002.

on the wave function. This means that when the wave function is sharply peaked in a volume of configuration space associated with a particle, then it is located in that region.

The single dynamical law of the SL approach says that the wave function of an isolated system evolves in conformity with a probabilistic law that specifies (depending on the wave function at *t*) the chances of various wave functions at subsequent times. More precisely the wave function evolves in accordance with Schrödinger's deterministic equation except that at any given time there is a chance that the function will collapse into a narrower wave function. This collapse is a physical process, a "hit" or a "jump"; a part of the wave function, not something else; it has a precise measure and it occurs at a precise rate, one which is proportional to the mass density of the system.

The wave function is also a mathematical construct which is composed of expectation values, or probabilities. Probabilities of what, exactly? Neither of getting, or *finding,* a value when a quantity is measured, nor of the quantity measured *having* the considered value, but rather the SL approach has a different story, which draws on Schrödinger's original interpretation of the wave function as a *density* function:

> In the beginning, Schrödinger tried to interpret his wavefunction as giving somehow the density of the stuff of which the world is made. He tried to think of an electron as represented by a wave packet—a wave function appreciably different from zero only over a small region of space. The extension of that region he thought of as the actual size of the electron—his electron was a little bit fuzzy. At first he thought that small wavepackets, evolving according to the Schrödinger equation, would remain small. But that was wrong. Wavepackets diffuse, and with the passage of time become indefinitely extended, according to the Schrödinger equation. (Bell 1990, 39)

Following Schrödinger, the SL approach views the wave function as giving the density of the "stuff" the world is made of in a multidimensional configuration space. What the theory is about, what is real "out there" at a given spacetime location x, is just the average mass density in the characteristic volume around x.

In trying to make sense of the this interpretation the SL approach introduces an accessibility criterion which simply states that a property corresponding to a value of a certain variable is objectively possessed or accessible when any experiment (or physical process) yielding reliable information about the variable, would, if performed, give an outcome corresponding to the claimed value (Ghirardi 1997). Now, the character of the SL theory is such that the average mass density is *not* an accessible property of both microscopic and macroscopic objects: a microscopic system, unless its wave function is localized better than a certain quantity defined by the theory, has almost always an *inaccessible* average mass density. A macrosystem, on the other hand, has almost always an *accessible* average mass density, and hence can be described in classical terms.

Thus the quantum "weirdness," or quantum non-separability, is, in this case, *ontologically* construed. This is exactly the issue on which Einstein and the SL approach disagree. Einstein objected to the Copenhagen worldview: it only makes statements about what one will find if . . . , not what *is*. The SL approach accepts Einstein's position but restricts it to the classical realm, i.e., along with John Bell it rejects the arbitrariness of the "shifty split" between the classical and the quantum and offers not just vague words but precise mathematics to tell us what is system and what is apparatus, and which natural processes have "the special status of measurements" (Bell 1990, 34). The idea here is that the collapse of the wave function is a natural mechanism that permits "electrons and photons to enjoy the cloudiness of waves, while allowing tables and chairs to be described in classical terms" (Bell 1987, 190). Thus any embarrassing macroscopic ambiguity is only momentary in the SL theories, and non-separability of macrosystems is physically ruled out. The division of the world, rather than being conventional or arbitrary, is a natural consequence of the theory. For this reason the realism of the SL approach is best viewed as "macro-realism" (Ghirardi 2000), a position Einstein found hard to accept:

> The macroscopic and the microscopic are so inter-related that it appears impracticable to give up this program [of a realistic description in space and time] in the microscopic alone. (Einstein in Schilpp 1949, 688)

But perhaps this is the price of an acceptable realism.

5. A Joke Should Not Be Repeated Too Often. In this paper I have tried to show that no matter how interesting they are, the suggestions to reformulate the axioms of QM in information-theoretic terms cannot be regarded as supplying a realistic foundation to QM. Fuchs' "thin" realism, and the entire "fog from the north" which inspires it,[26] are nothing but instrumentalism in disguise. Of course there would be no science without scientists but this does not mean that the ultimate subject matter of science is the scientist and his relation to the world, no matter how sensitive the latter is to his touch.

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[26] Fuchs (2001b, 7) cites John A. Wheeler in a letter to the *New York Times:* "It may be, as one French physicist [here Wheeler refers to de Broglie] put it, 'the fog from the north,' but the Copenhagen interpretation remains the best interpretation of quantum mechanics that we have."

It is interesting that Einstein, having understood that the motivations underlying his theories of relativity led to philosophical bankruptcy when quantum mechanics was discovered—hence his famous EPR argument and his antipathy to the anti-realist interpretations of Bohr, Heisenberg, and almost all of the members of physics community —abandoned this "new fashion" in favour of realism. Einstein's colleagues, immersed as they were in the Kantian state of mind, refused to understand how, having started this fashion in 1905, Einstein could possibly reject it twenty years later. Einstein's words to his friend Philip Frank clearly reveal his insight:

> Yes, I may have started it, but I regarded these ideas as temporary. I never thought that others would take them much more seriously than I did . . . A joke should not be repeated too often. (Clark (1971, 340) cited in Bechler 1999, 352)

As shown here, there is no need to completely override Einstein's insight in light of QM or QIT. One can follow it up to a point, acknowledging quantum incompleteness as a feature of the micro-world while maintaining macro-realism and demonstrating how the latter arises from the former in a precise, observer-independent, and natural way.

The standard measurement problem infects *all* quantum theories, be they quantum field theories (see, e.g., Clifton and Halvorson 2002, 28), quantum cosmology (see, e.g., Bell 1987, 117–138), or, as we have seen, quantum information theory, and yet no one can plausibly argue that in order to make progress in these fields the measurement problem must be solved. Matters are quite different, however, when one ignores the measurement problem and claims further to have made progress in foundational issues. I am afraid the taxpayer will have to find someone else to rely on in relieving himself from the burden of financing conferences on quantum foundations.

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