# Is Measurement a Black Box? On the Importance of Understanding Measurement Even in Quantum Information and Computation

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It has been argued, partly from the lack of any widely accepted solution to the measurement problem, and partly from recent results from quantum information theory, that measurement in quantum theory is best treated as a black box. However, there is a crucial difference between 'having no account of measurement' and 'having no solution to the measurement problem'. We know a lot about measurements. Taking into account this knowledge sheds light on quantum theory as a theory of information and computation. In particular, the scheme of 'one-way quantnum computation' takes on a new character in light of the role that reference frames play in actually carrying out any one-way quantum comptuation.

**1. The 'Black-Box' View of Measurement.** Measurement is often treated as a 'black-box' in quantum theory, in the sense that one often does not worry about the physics of a given measurement. Instead, one characterizes measurement in terms of some operator on a Hilbert space. One may then let the structure of the theory in Hilbert space take over from there.

It is not always wrong to do so. The structure of Hilbert space (or more abstractly, $C^*$-algebras) *is* important. There is good reason to take it as 'given', to use that structure in our representations of measurement and our analysis of those representations. At least two reasons have been offered in the literature for a stronger claim, namely, that measurement should always (at least for now) be treated in this way. Perhaps unsur-

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prisingly, these reasons have been offered by people working in theoretical quantum information and quantum computation, where measurement is often treated as a black-box.

The first reason arises from Fuchs's (2003) suggested program for the foundations of quantum theory:

> Our foremost task should be to go to each and every axiom of quantum theory and give it an information theoretic justification if we can. Only when we are finished picking off all the terms (or combinations of terms) that can be interpreted as subjective information will we be in a position to make real progress in quantum foundations. The raw distillate left behind—minuscule though it may be with respect to the full-blown theory—will be our first glimpse of what quantum mechanics is trying to tell us about nature itself.

Set aside issues about the nature of the physical world and focus, for now, on figuring out how much of the formal structure of quantum theory can be understood in purely information-theoretic terms. Fuchs's main argument for this approach is twofold: other approaches (i.e., other programs for the interpretation of quantum theory) have largely failed; and some promising progress has been made in Fuchs's positive program.

The second reason for setting aside the issue of the physics of measurement (in foundational discussions—nobody is suggesting that the issue should be dropped in all contexts) comes from Bub (2004):

> A mechanical theory that purports to solve the measurement problem is not acceptable if it can be shown that, in principle, the theory can have no excess empirical content over a quantum theory. By the CBH [Clifton, Bub, and Halvorson (2003)] theorem, given the information-theoretic constraints any extension of a quantum theory . . . must be empirically equivalent to a quantum theory, so no such theory can be acceptable as a deeper mechanical explanation of why quantum phenomena are subject to the information-theoretic constraints. To be acceptable, a mechanical theory that includes an account of our measuring instruments as well as the quantum phenomena they reveal (and so purports to solve the measurement problem) must violate one or more of the information-theoretic constraints.

The information-theoretic principles to which Bub refers are, roughly: No superluminal transfer of information, no unconditionally secure bit commitment, and no cloning of states. So long as we assume these principles (and they are true as far as we know), then the CBH theorem implies that any theory (more precisely, any theory formulatable in roughly $C^*$-

algebraic terms[1]) we might come up with will be observationally the same as quantum theory. Bub concludes:

> The rational epistemological stance is to suspend judgement about all these empirically equivalent but necessarily underdetermined theories and regard them all as unacceptable. It follows that our measuring instruments ultimately remain black boxes at some level that we represent in the theory simply as probabilistic sources of ranges of labelled events or 'outcomes'.

In other words, the empirical 'essence' of quantum theory can be captured in information-theoretic terms, terms that in fact treat measurement as a black-box.

While I have sympathy with much of the motivation behind this argument, I have two objections. The first, which is not my main concern here, concerns the grounds we have for believing in the information-theoretic principles themselves. Prior to the discovery that these principles are true in quantum theory, we had no reason to believe them (and indeed classical mechanics gave us some reason for denying at least some of them). And if quantum theory goes by the wayside, then the reason for believing them does as well. (Of course, other reasons might arise.) In other words, it is slightly odd to take those principles as somehow more secure than quantum theory itself.

However, the main point here is that one can agree that we cannot (or perhaps are unlikely to) provide a completely satisfactory account of measurement that is wholly internal to the theory, without also agreeing that we can say *nothing* about measurements, that measurements are black-boxes. Indeed, in the remainder of this paper, I will argue that we can say quite a bit—even at the foundational level—about measurements, and that it is in fact important to do so, *even* in the context of quantum information and computation. I will focus on 'one-way' quantum computation. However, I claim (here, without argument) that similar consideration apply to the circuit model of quantum computation, as well as to quantum information.

**2. What Is It to Be 'an Observer of *X*'?** Here is a foundational question: What does it mean to 'be an observer of *X*', where *X* is some physical quantity? (Why do I claim that the question is 'foundational'? See Section 4.) By 'observer' here I refer not only to agents, but also to devices that are capable of making 'observations'. There are many components to a

1. The class of such theories is broad. Whether the class of all such theories is broad *enough* to include all 'plausible' physical theories is questionable—my own view is that it is not.

complete answer (and I do not claim to know what they all are), including, perhaps, the capacity to keep records. Here I focus on two related points, both of which are themselves connected with the fact that quantum-theoretic observables are definable in group-theoretic terms: physical quantities are reference-frame-dependent; and a procedure of observation is legitimate only if it is seen as such from within an inertial frame, that is, a frame in which the law of motion (e.g., Schrödinger's equation) is true.

The first point—perhaps better characterized as a controversial claim—is that observations are always made in the context of some frame of reference, which in part defines which observation has in fact been made. I cannot argue the claim in detail, here, but I will make a few points to support it.

The claim is quite clearly true for observations of, say, position and momentum. It is a familiar fact that those physical quantities are always defined relative to a spatio-temporal frame of reference, normally itself taken to be defined by the apparatus that performs the measurement, and in any case, if it is to be empirically accessible, must be defined by some physical body whose spatio-temporal relationship to the apparatus is known.

The claim extends to other observables, differently in different cases. For some observables, there is another sort of frame of reference that does the job; for example, in order to measure 'spin in the $z$-direction', one must specify a frame of reference that fixes 'the $z$-direction', typically by specifying some physical body that defines an orientation in space. For some other observables, which we might call 'frame-independent quantities' (analogous to the space-time interval $\tau = \sqrt{t^2 - (x^2 + y^2 + z^2}$, for example), I claim that the observable is measured only by first measuring some frame-dependent quantity or quantities, and then calculating the value of the absolute quantity. (Consider, for example, how one might go about measuring $\tau$.) On this view, the existence of frame-independent quantities in a theory reflects the possibility and means of communication and agreement across different frames, but these quantities are not considered to be directly empirically accessible. (See Dickson 2007, Section 3.)

The second point is that procedures of observation should be described by the laws of the theory, at least in the sense that the laws tell us that the procedure is indeed a valid procedure for observing the quantity in question. Einstein reportedly said that "it is the theory that decides what we can observe" (see Heisenberg 1969, 46). Here we are going a step further (though this point could well have been what Einstein had in mind): It is the theory that decides *how* we can observe. This 'decision' is made by an application of the physical laws, and of course that application must happen in a frame in which the laws are in fact true, an 'inertial frame'.[2]

In fact, the situation is somewhat worse, because we can never be certain that we know of *any* exactly inertial frame. Nonetheless, we can imagine knowing of one, and consider what our actual situation would look like from the point of view of this exactly inertial frame—call it 'the privileged frame'—by means of an imagined transformation from our frame to it. (See Dickson 2004 for detailed discussion.)

This imaginative procedure is in fact what makes it clear that when we measure, say, position, we are *in fact* measuring a *relational* observable, one that is defined relative to a frame of reference, and if it is to be observationally meaningful, relative to some physical system that is somehow definitive of the frame in question. For example, in quantum theory, we typically represent the position observable with some apparently 'absolute' observable, $Q$, on a Hilbert space, whose spectrum is just 'the possible positions' of a system. But from within the privileged frame it will be clear that we are in fact measuring a relational observable. Indeed, Aharonov and Kaufherr (1988) have written down the appropriate transformations from the observer's frame to the privileged frame, and those transformations take an observable like $Q$ to an observable like $Q_0 - Q_1$, where $Q_0$ is the privileged frame's observable for the position of the body that defines position for the observer, and $Q_1$ is the privileged frame's observable for the position of the system whose position is being observed.

As I mentioned above, these points are related to a fundamental fact about quantum observables, which is that they can be defined in terms of symmetries. In rough outline, here is how it works. (For details, consult, e.g., Busch et al. [1995] or Varadarajan [1985].) Consider an observable to be a map (POVM), $E : \mathcal{B}(S) \to \mathcal{L}(H)$, from the Borel subsets of some 'spectrum' (of possible values of the observable) to positive operators on a Hilbert space, $H$. (They are spectral projections if we are talking about an observable that can be represented as a self-adjoint operator, in which case each Borel subset of the spectrum gets mapped to the associated member of the spectral family.) Consider a symmetry implemented in terms of a representation of a group, $G$, as a group of unitary operators, $U_g$ (for $g \in G$), on $H$. Let the action of $G$ on the spectrum of the observable be given by $a_g$ (for $g \in G$). Then we say that the observable $E$ is 'invariant' under this symmetry if $U_g E(\Delta) U_g^{-1} = E(\Delta)$ for any $\Delta \in \mathcal{B}(S)$ and any $g \in G$. We say that $E$ is 'covariant' under this symmetry if

2. The justification for thinking of inertial frames as frames in which the basic laws of motion hold is convoluted. See Barbour (1989) and DiSalle (1991, 2002). For convenience, we often work in some noninertial frame, but we can do so successfully only because we know how that frame is related to an inertial frame.

$U_g E(\Delta) U_g^{-1} = E(a_g \Delta)$. For example, position is covariant under spatial translation and invariant under boosts. (Note that the relational version of a covariant observable is invariant. For example, a relational position observable is not covariant, but invariant, under spatial translations.)

Mackey's (1949, 1978) imprimitivity theorem implies, in essence, that there are (up to irrelevant unitary transformations) *unique* observables that satisfy certain invariances. For example, the position and momentum observables in nonrelativistic quantum theory are uniquely picked out by the symmetries that they obey. On the present view, this mathematical fact reflects a physical fact, namely, that observable quantities are frame-dependent in the ways described above.

The discussion above suggests the following requirement for 'being an observer of $X$' (and in this context, I will not be able to do more than provide suggestive discussion on this point):

> $F$ (a frame of reference, as determined, in some specified way, by a physical system) is an *observer of* $X$ (during the time $\Delta t$) if one can define, in $F$, some observable, $\hat{X}$, such that the transformation of $\hat{X}$ to some inertial ('privileged') frame (during $\Delta t$) is a relational observable satisfying the invariances that are definitive of $X$.

It is, perhaps, a bit odd to refer to a frame of reference as an 'observer', but the point should be clear. Observations happen within a frame, and the question here is really whether a given frame is a suitable point from which to make observations of $X$. For any given $X$, of course, more work needs to be done; in particular, one would need to determine which invariances (symmetries) define $X$. Furthermore, one would need to know that the apparatus that actually does the observing is related to the body or bodies that define the frame in the right way. (More often, however, the apparatus itself is the body that defines the frame, so that the question then just becomes whether we are in a position to define the relevant observable.)

A great deal follows from this (partial!) conception of observation. In particular, the uncertainty relations between various pairs of observables follows directly (Busch et al. 1995 and Varadarajan 1985) from Mackey's Theorem and Stone's Theorem, plus a few further technical assumptions[3] Moreover, the requirement that our actual procedures be validated from the privileged frame implies that, at least in some simplified models of measurement, a measurement of an observable, $F$, disturbs the value that the physical body defining the reference frame that defines $F$ has for

3. I some contexts these assumptions are controversial—see Halvorson 2004 for doubts about the regularity assumption, for example.

observables that do not commute with $F$. (See Dickson 2004 for mathematical details, and Section 4 below for an important qualification.)

In other words, we can say a great deal about how observation works in quantum theory. We can do so by appeal to, among other things, quantum theory itself. And we can do so *despite* the fact that no fully satisfactory solution to the measurement problem is on offer. Below I will argue that the sorts of of things that we can say about measurement are part of the foundations of quantum theory. I will also make the case, by way of an example, that this sort of foundational discussion of observation can be very important in the context of quantum computation and information.

**3. One-Way Quantum Computation.** 'Traditional' quantum computation (Nielsen and Chuang 2000) is normally conceived in terms of an 'input', a sequence of operations (representable, e.g., in terms of logical 'gates') performed on the input, and a resulting 'output'. The sequence of operations instantiates some algorithm that solves the computational problem at hand, for example, searching for a given item in an ordered list, or factoring a number. In classical computation, the input is an ordered set of bits (e.g., a binary representation of the number to be factored), as is the output.

In traditional quantum computation, the input is an ordered set of 'qubits', (represented by statevectors in $\mathbb{C}^2$, normally all taken to be the state $|0\rangle$ relative to some appropriate basis, $\{|0\rangle, |1\rangle\}$), the logical gates are unitary transformations (on $n$-tuples of the qubits, so in general represented by unitary operators on some $n$-fold tensor product of $\mathbb{C}^2$ with itself), and the output is given by some ordinary (projective) measurement performed on some or all of the qubits after they have all passed through the quantum gates. In this scheme, measurement is largely if not entirely a black-box affair. In addition to finding an interesting algorithm, the difficulty that is considered most often concerns implementation of the required unitary transformations, avoiding, for example, interactions with the environment.

So-called one-way quantum computation (Raussendorf and Briegel 2001; Raussendorf et al. 2003) is computationally equivalent to quantum computation, in the sense that any algorithm that is implementable by a traditional quantum computer is also implementable with equal efficiency by a one-way quantum computer. However, the model is, on the face of it, entirely different: a set of qubits (conceived as organized into some $N$-dimensional lattice) is prepared in some initial (normally highly entangled) state. Then a sequence of projective measurements is made on subsets of the initial set of qubits, and the sequence of results of these measurements eventually delivers the answer to the problem.

Although generic accounts are available, I will approach it here in terms of just about the simplest example. Choose some basis (the 'computational basis'), $\{|0\rangle, |1\rangle\}$, for $\mathbb{C}^2$, and define $|\pm\rangle = |0\rangle \pm |1\rangle$. Define the (unitary) 'controlled phase' operator by

$$CZ|i\rangle|j\rangle := (-1)^{ij}|i\rangle|j\rangle \tag{1}$$

(with $i, j$ each 0 or 1). Now consider a 'lattice' (in this case, a very simple lattice) of three qubits—labeled 1, 2, and 3—in the initial state $|\psi\rangle|+\rangle|+\rangle$, where $|\psi\rangle$ is some arbitrary state $|\psi\rangle = a|0\rangle + b|1\rangle$. The first stage of the one-way quantum computation is the preparation, in which we create, from this product state, some appropriate entangled state, typically by means of one or more applications of $CZ$ to pairs of particles (written here as $CZ_{mn}$ when applied to particles $m$ and $n$). By an application of $CZ_{12}$, then, the state $|\psi\rangle|+\rangle|+\rangle$ becomes

$$(a|00\rangle + a|01\rangle + b|10\rangle - b|11\rangle)|+\rangle \tag{2}$$

(writing $|i\rangle|j\rangle$ as $|ij\rangle$). Notice that this state is entangled (in the first two particles).

Following the description above of one-way quantum computation, we should now finish the preparation, by an application of $CZ_{23}$ to (2), thereby producing a completely entangled state, obtained by entangling 'nearest neighbors' in the initially unentangled lattice of qubits. Then begins stage two, the sequence of projective measurements on qubits in the lattice.

These projective measurements will be of observables whose eigenstates are, ignoring normalization, $\{|0\rangle \pm e^{i\theta}|1\rangle\} := M(\theta)$, for some $\theta \in [0, 2\pi)$. The entangling operations (applications of $CZ_{mn}$) commute with these measurements, so that we can equivalently consider an alternating sequence of entanglements followed by measurement. This way of proceeding turns out to be slightly easier calculationally.[4]

So after the application of $CZ_{12}$, resulting in (2), suppose that we mea-

4. The order of presentation here is the reverse of the way it is often presented. Typically, expositors begin with the idea of an alternating sequence of entanglements and measurements, then note that these operations commute, and point out that we can therefore perform all of the entanglements followed by all of the measurements. The proposed implementations of one-way quantum computation proceed in that order (all of the entanglements followed by all of the measurements), and indeed the entanglements are often described as occurring all together, in a single physical operation.

sure in the basis $M(\theta)$, and get the result $|0\rangle + e^{i\theta}|1\rangle$. The state is then (after the usual application of the projection postulate)

$$\begin{aligned}(|0\rangle + e^{i\theta}|1\rangle)(a|+\rangle + e^{-i\theta}b|-\rangle)|+\rangle \\ = (|0\rangle + e^{i\theta}|1\rangle)W(-\theta)|\psi\rangle|+\rangle\end{aligned} \tag{3}$$

with (again, up to a normalizing factor)[5]

$$W(\theta) = \begin{pmatrix} 1 & e^{i\theta} \\ 1 & -e^{i\theta} \end{pmatrix}. \tag{4}$$

Note that $W(\theta)$ is unitary. Now apply $CZ_{23}$ in order to entangle particle 2 with particle 3 and (3) becomes

$$\begin{aligned}(|0\rangle + e^{i\theta}|1\rangle)W(-\theta) \\ \times[a(|00\rangle + |01\rangle + |10\rangle - |11\rangle) + e^{-i\theta}b(|10\rangle + |01\rangle - |10\rangle + |11\rangle)].\end{aligned} \tag{5}$$

Now suppose that we measure in the basis $M(\phi)$, and get the result $|0\rangle + e^{i\phi}|1\rangle$. The state is then

$$(|0\rangle + e^{i\theta}|1\rangle)(|0\rangle + e^{i\phi}|1\rangle)W(-\theta)W(-\phi)|\psi\rangle \tag{6}$$

(again, after projection).

Notice what has happened here: the initial state of the first qubit in the lattice has been 'almost copied' to the final (third) qubit. One can therefore think of this procedure as implementing a kind of 'copying algorithm'. It is similar to quantum teleportation, of course, and is often presented in those terms (though there are important differences between this scheme and the standard scheme for quantum teleportation).

I say 'almost' copied because of course the state of the final system is not $|\psi\rangle$, but $W(-\theta)W(-\phi)|\psi\rangle$. However, in principle there is no problem here. We just need to keep track of $\theta$ and $\phi$, then apply the appropriate (inverse) transformations to the final system to get it into the state $|\psi\rangle$.

The need to perform these final transformations on the output state is not unique to this particular scheme. It is characteristic of one-way quantum computation that the final output state is obtained only after one or more (typically *many* more than one) such transformations are performed.

**4. The Role of Observers in One-Way Quantum Computation.** The scheme of one-way computation has a *prima facie* advantage over traditional quantum computation. Recall one difficulty faced by traditional quantum

5. We are adopting the following matrix representation of $|0\rangle$ and $|1\rangle$:

$$|0\rangle \mapsto \begin{pmatrix} 1 \\ 0 \end{pmatrix} \; |1\rangle \mapsto \begin{pmatrix} 0 \\ 1 \end{pmatrix}.$$

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computers: implementing the unitary gates while preventing the significant interaction with the environment. The reason that such interaction is a problem is that it gives rise to decoherence, which effectively destroying the entanglement that is essential for quantum computation.

In a one-way quantum computation, there *are* some unitary transformations that must occur, as we have seen, but the story here is somewhat different. The initial entanglements amongst particles in the lattice (represented by applications of $CZ_{mn}$) are believed to be implementable physically (e.g., by means of quantum Ising interactions in the lattice). The final transformations ('undoing' the $W(-\theta)W(-\phi)$ in the example above) are applied after the computation has occurred, and in fact the entanglements are not even in place any more, because the measurements disentangle the particles—compare, for example, (5) with (6). So it appears that the difficulties presented by environmentally-induced decoherence do not arise, or are not as serious, in this case.

But our analysis of observation above reveals a different sort of difficulty for the one-way scheme: each measurement in the basis $M(\theta)$ is a frame-dependent observation, and in particular the frame must establish what is meant by $\theta$. The same goes, of course, for subsequent measurements in other bases, $M(\phi)$, and so on.

How will the '$\theta$ frame' be established? First, some frame must establish the physical meaning of the 'computational basis' $\{|0\rangle, |1\rangle$. Some physical object will do so, by picking out a direction in space corresponding to $\{|0\rangle, |1\rangle\}$. Other bases, $M(\theta)$, are then defined in terms of angles away from the direction associated with the computational basis. Our frame of reference, then, consists of a physically indicated direction in space, and a physical indication of various angles away from that indicated direction.

As noted above, the investigation of what it takes to make an observation reveals that normal, 'impulsive', projective, observations (as in Bohm 1951, Chapter 22) of an observable, $X$, disturb the frame, and in particular disturb the values that it has for observables that are 'incompatible' with the measured observable.

The notion of 'incompatibility', here, needs some explanation. If the observables in question are position and momentum, then the position and momentum of the frame itself are taken to define what is meant by 'position' and 'momentum'. Hence, for example, if we measure the position of some particle relative to this frame, we will disturb the momentum of the frame itself, and indeed it is this disturbance that renders the particle's momentum (relative to the frame) uncertain after the measurement of its position. However, in other cases, the frames are definitive of observables in a somewhat different way. In the case of spin, as we noted above, a frame consists of a direction in space and angles away from that direction. As it happens, these two quantities are themselves incompatible—there is an uncertainty relation between 'direction in space' and 'angle'.[6] And when we measure an observable whose definition relies on this frame, we disturb the value that the frame itself has for one or the other (or both) of these observables.

Now we have a problem. In a one-way quantum computation of any serious complexity, we will make many measurements in many different bases $M(\theta)$. Each one renders us a little bit less certain about what even *counts* as a given direction in space (those given by $M(\theta)$, $M(\phi)$, etc.). But to the extent that we are uncertain about what even counts as 'the $M(\theta)$-direction', we will be inexact in our final application of the $W(-\theta)$, $W(-\phi)$, and so on, at the end of the computation. How serious will this effect become? I am unaware of any attempt to calculate it; our theoretical situation, here, is thus analogous to the situation with respect to decoherence prior to the detailed theoretical (including calculational) work done, for example, by Zurek (1982), Leggett (1984), Joos and Zeh (1985), and many others.

As in the case of preventing interaction with the environment in traditional quantum computation, the problem here is not a problem in principle. There *is*, in others words, a solution *in principle*, suggested by the case of position and momentum measurements. For suppose that some physical body, say, an optical bench, defines a frame of reference relative to which we will measure the position of some particle. Making this measurement will disturb the momentum of the bench, thus disturbing, as Bohr (1935) said, "the very conditions that define the possible types of predictions regarding the future behaviour of the system"—in this case, conditions regarding momentum (as defined relative to the bench). But there is a well-known solution to the problem: we can track the change in momentum of the bench from the point of view of some other, 'encompassing', frame, for example, the frame given by the center of mass of the laboratory, or the tree outside, or the moon, or whatever, so long as we have some reason to believe that we know how the object in question (lab, tree, or moon) is related to some inertial frame, some frame in which the law of motion—Schrödinger's equation—is true.

Return now to the case of spin measurements in bases $M(\theta)$ for various $\theta$. Each of these measurements disturbs the frame that defines directions in space. However, keeping track of all such disturbances by means of encompassing frames, we could then reconstruct the directions in space

6. See Busch et al. 1995 for mathematical details. The basic idea is to let 'direction in space' be defined by an angular momentum, $L_z$, of some object (which would thus define 'the $z$-direction'). Then define an angle observable in a straightforward trigonometric way. The result is canonically conjugate to $L_z$, in the sense of the Weyl relations.

picked out by our various measurements, and implement the final transformations ($W^{-1}(\theta)$, $W^{-1}(\phi)$, etc.) accordingly.

Hence the issue that I am raising is not an insurmountable problem—and no doubt there are other, more creative, solutions than the straightforward solution I mentioned above. Still, I claim that we have learned an important lesson, here, namely, that we black-box measurement at our peril. Let me return, now, to the original arguments from Fuchs and Bub in *favor* of black-boxing, and say where I think they may mislead.

To be fair, Fuchs's remarks are perhaps not intended so much as an argument as the articulation of a program, perhaps with the suggestion that the program is the best strategy we have, at this point, for pursuing foundational work in quantum theory. My approach here will be to consider the suggested program.

Recall Fuchs's basic idea: interpret each of the axioms of quantum theory information-theoretically; the remainder is 'what quantum mechanics is trying to tell us about nature itself'. (Bub does not explicitly endorse the latter part of the idea, and indeed this difference marks a crucial if sometimes overlooked point of contention between them; see Groover 2008.) This strategy will resonate with any classical information theorist. Classical information theory is typically not concerned with the manner in which information is physically encoded; it abstracts from physical encoding, and seeks to demonstrate general truths about (typically, constraints on) the accuracy of transmission and degree of compression of information, regardless of how it is physically encoded. Fuchs's (and Bub's) suggestion is to treat quantum theory as a theory of information along similar lines, that is, as a theory of information abstracted from physical implementation.

Recall, now, that we are talking about *foundational* issues. It would be pointless, or at least hopeless, to advocate that all physicists who currently work on quantum theory begin working information-theoretically. Current work on, say, the quantum mechanics of semiconductors is unlikely to be helped much, if at all, by taking an information-theoretic approach. Indeed, there is an undeniable 'material', 'concrete', component of such work that is essential to the enterprise—one cannot 'abstract' to the purely information-theoretic content and still be studying semi-conductors. But presumably Fuchs and Bub do not intend their message for those working in such fields, but instead for those of us who worry about the foundations of quantum theory, and I will take it as such.

The analysis, above, of the role of observers in one-way quantum computation suggests a reason for denying that quantum information is all there is (for now) to the foundations of quantum theory. In short, the reason is this: observation (measurement) is an essential part of quantum information and quantum computation, and the nature of observation is itself a foundational issue, and moreover, an issue to which the theory itself speaks. I'll conclude by fleshing out this point.

In classical information theory and classical computation theory, observation plays some sort of role, but it is not really a 'part' of the theory. A Turing machine must 'read' the symbol on the tape in order to proceed, but the theory of Turing machines says nothing about how these observations occur, or the conditions under which they are possible, or anything of the sort. In order to compress or decompress some stream of data, the stream must be 'read', but information theory has nothing to say about 'reading data'. Such operations (the production and reading of data, the reading of symbols in a computation, etc.) truly are black-boxed within these theories, and rightly so, for the theories have absolutely nothing to say about them.

But in quantum theory, the situation is different. Quantum theory *does* have something to say about observation, about how observation occurs, the conditions under which it is possible, and the *in principle* consequences of making an observation. True, there is a major problem (the measurement problem) lurking in the wings (or slapping us in the face), but this problem, difficult and troublesome and unresolved as it may be, does not imply that nothing can be said *from within the theory* about observation. My remarks above were meant to indicate, in outline at least, some things that can be said about observation from within the theory. And notice that having said them, we thereby learned something about one-way quantum computation.

Were the things that I said about observation 'foundational'? In part, perhaps, the answer to this question is a matter of taste, but in defense of a 'yes', let us notice three things. First, the conclusions suggested there are based on the same sorts of mathematical facts (the structure of Hilbert space in particular) that are taken by Fuchs and Bub to be at the heart of the theory, and whose interpretation is taken (by Fuchs at least) to be a foundational matter. Second, those conclusions are intimately tied up with the uncertainty principle, the understanding of which has at least traditionally been taken as part of the foundations of the theory. Third, quantum theory itself is historically part of the tradition of empirical science, which has traditionally been understood as *essentially* beholden to empirical observation. Therefore, understood in this historical context at least, it hardly seems plausible to deny that understanding the role of observation in the theory could be anything other than foundational. Einstein suggested that theories determine what can be observed. I am suggesting that understanding *how* they do so is part of the project of understanding them foundationally. I am also suggesting that this project is not hopeless.

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