[DRAFT]

Is Measurement a Black Box?

On the Importance of Understanding Measurement Even in Quantum Information and Computation

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Abstract

It has been argued, partly on the grounds that no decent solution to the measurement problem seems to be forthcoming, and partly on the grounds of recent results from quantum information theory, that measurement in quantum theory is best treated as a black box, and quantum theory itself is best treated as a theory of information and computation. I agree with the premises of the argument, but not the conclusion. In particular, there is a crucial difference between 'having no account of measurement' and 'having no complete account of measurement that is entirely internal to the theory' (i.e., having no solution to the measurement problem). In fact, we know quite a bit about measurements. In this paper, I will argue that taking into account some of what we know about measurements—in particular, the role of reference frames in measurements—sheds some light on quantum theory as a theory of information and computation. In fact, the recently proposed 'one-way quantnum computation' scheme takes on a new character in light of the role that reference frames must play in the actually carrying out of any one-way quantum comptuation.

1 The 'black-box' view of measurement

Measurement has often been treated as a 'black-box' in quantum theory. In particular, one (if one is a philosopher!) very seldom worries about the physics of a given measurement. Instead, we characterize measurements in terms of some operator on a Hilbert space, and take it from there.

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It is not always wrong to do so. There is very good reason to believe that the structure of Hilbert space *is* important. There is very good reason to take it as 'given', to use that structure in our representations of measurement and our analysis of those representations. (One might prefer to discuss instead the structure of C^*-algebras, or perhaps some more exotic algebras, but the essential point here remains the same.)

Indeed, 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 unsurprisingly, these reasons have been offered by people working in quantum information and quantum computation, where measurement is almost universally treated as a black-box.

The first reason arises from Fuchs' (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—miniscule 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.

The idea, then, is to 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' main argument for this approach is twofold: first, other approaches (that is, other programs for the interpretation of quantum theory) have largely failed, and second, some promising progress has been made in Fuchs' 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. But the details are not important here. Bub's point is that 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 empirically (experimentally) the same as quantum theory. Bub concludes:

> [T]he 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

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[1] The class of such theories is broad, and includes, for example, classical mechanics, although classical mechanics is excluded, here, because it does not obey the information-theoretic principles in question. Whether the class of all such theories is broad *enough* to include all 'plausible' physical theories is an issue that I shall not pursue here.

> 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, let us set this perhaps minor complaint aside. The main point here is that one can agree that we cannot (or perhaps less dogmatically, 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 an example from quantum computation, namely, the recently proposed scheme of 'one-way' quantum computation. However, I claim (here, without argument) that similar consideration apply to traditional 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 §4.) By 'observer' here I do not necessarily refer only to agents such as people, but also to devices that are capable of making 'observations'. There are many components to a complete answer (and I do not claim to know what they all are), including, perhaps, the capacity to keep records, for example. Here I will focus on two related points, both of which are themselves connected with the fact that quantum-theoretic observables are definable in group-theoretic terms. The first point is that physical quantities are reference-frame-dependent. The second point is that 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. I'll now consider these points in a little more detail.

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 what 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.

My claim extends to other observables, however, although 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', we need to specify a frame of reference that fixes what is *meant* by '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), the claim is 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 τ.) 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.

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". 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] (For example, in Newtonian mechanics, it must happen in an inertial, i.e., non-accelerating, frame.) For convenience, we often work in some non-inertial frame, but we can do so successfully only because we know how that frame is related to an inertial frame. (For example, in Newtonian mechanics, a rotating frame gives rise to fictitious Coriolis forces, which would ruin our application of the laws of motion if we did not *know* that the frame is in fact rotating.)

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

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[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).

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 'really' measuring a relational observable. Indeed, Aharanov 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, for example, 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 $U_g E(\Delta) U_g^{-1} = E(a_g \Delta)$. For example, position is covariant under spatial translation and invariant under boosts.

In fact, we can simplify matters a bit in light of our earlier discussion. If it is correct that all observables are relational, then we need not worry about covariance, for suppose that E (an observable as written down by the inhabitant of some frame) is covariant under the symmetry described by G. Then we can consider the 'same' observable from the point of view of the privileged frame. As noted above, it will have a relational form, and in that form, it will be invariant under G. Consider the obvious case of position. A relational position observable is not covariant, but invariant, under spatial translations.

Now, Mackey's imprimitivity theorem tells us, in essence, that there are (up to irrelevant unitary transformations) *unique* observables that satisfy certain invariances. For example, the position and momentum observables in non-relativistic 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 Δt) if one can define, in F, some observable, $\hat{X}$, such that the transformation of $\hat{X}$ to some inertial ('privileged') frame (during Δt) 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 (though in some contexts they are controversial—see Halvorson (2004) for reasons one might have for questioning the regularity assumption, for example). 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 observables that do not commute with F. (See Dickson 2004 for mathematical details, and §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, the sorts of things that I said above, as well as other things that follow from the general analysis of observation that I've given above and things that follow from the analysis of particular observables in terms of symmetries (invariances), 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 quatum computation

'Traditional' quantum computation[3] is normally conceived in terms of a model not unlike the model of standard, classical, computation, where there is an 'input', a sequence of operations (representable, for example, in terms of logical 'gates') performed on the input, with a resulting 'output'. The sequence of operations instantiates some

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[3] See Nielsen and Chuang (2000), for an extensive account, and numerous references.

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 (for example, a binary representation of the number to be factored), as is the output.

In traditional quantum computation, the classical input bits are replaced with a set of 'qubits', spin-$\frac{1}{2}$ systems (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 replaced with 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), called 'quantum gates', 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 general, the difficulties faced by those who seek to implement this scheme lie in the implementation of the unitary transformations. In particular, it is extremely difficult to ensure that the qubits undergo just the intended interactions (the ones represented by the quantum gates), and no others (for example, interactions with an environment).

So-called 'one-way' quantum computation[4] 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.[5] 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 a simple

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[4] See Raussendorf and Briegel (2001) and Raussendorf et al. (2003).

[5] 'With equal efficiency' is used here in the standard computer-theoretic sense; for example, if the traditional quantum computer can solve a problem in time polynomial in the size of the input, then a one-way quantum computer can do so as well, and so on for other 'speeds' (constant, linear, exponential).

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. (When CZ is applied to particles m and n, I will write it as CZ_{mn}.) By an application of CZ_{12}, then, the state $|\psi\rangle|+\rangle|+\rangle$ becomes

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

(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. (In more complicated computations, the lattice might be two-dimensional. Moreover, there are cases where it is expedient to destroy some of the systems in the lattice after this preparation, leaving 'holes' in the lattice. The present example requires neither of these complexities.) 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 $\theta \in [0, 2\pi)$—I will say that they are measurements 'in the basis $M(\theta)$'. 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.[6]

So after the application of CZ_{12}, resulting in (2), suppose that we measure 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):

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

with (again, up to a normalizing factor)[7]

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

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

$$\Big(|0\rangle + e^{i\theta}|1\rangle\Big)\, W(-\theta)\left[a\Big(|00\rangle + |01\rangle + |10\rangle - |11\rangle\Big) + e^{-i\theta}b\Big(|10\rangle + |01\rangle - |10\rangle + |11\rangle\Big)\right]. \tag{5}$$

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

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

(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).

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[6] 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.

[7] We are adopting the following matrix representation of $|0\rangle$ and $|1\rangle$:

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

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 θ and ϕ, 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 the difficulty with implementing an algorithm in a traditional quantum computer: it is very difficult to implement the unitary gates while preventing the qubits from significant interaction with the environment. The reason that such interaction is a problem is that it gives rise to decoherence, which effectively disentangles the qubits; but it is essential (for quantum computation) to maintain the entanglements amongst qubits during the 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 (for example, 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, eq. 5 with eq. 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 θ. The same goes, of course, for subsequent measurements in other bases, $M(\phi)$, etc..

How will the 'θ frame' be established? First, notice that the angle θ is not itself the direction in which spin is measured (if our qubits are spin-$\frac{1}{2}$ particles). Instead, the situation should be conceived as follows. Some frame must establish the physical meaning of the 'computational basis' $\{|0\rangle, |1\rangle$. Some physical object will serve this purpose, of course; it will pick out a direction in space, which we then take to be 'the direction in which spin is measured in a measurement of $\{|0\rangle, |1\rangle\}$'. 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',[8] projective, observations 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

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[8] I have in mind, here, a typical 'impulsive' model of measurement as given, for example, by Bohm (1951, ch. 22).

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'.[9] 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 $W(-\theta)$, $W(-\phi)$, etc., 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:

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[9] 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.

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 θ. 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 picked out by our various measurements, and implement the final transformations ($W^{-1}(\theta)$, $W^{-1}(\phi)$, and so on) 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 go wrong.

To be fair, Fuchs’ 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. (I’ve already indicated where I have doubts about Bub’s arguments for this program.)

Recall Fuchs’ 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.) 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' (and Bub's) suggestion is to treat quantum theory as a theory of information along similar lines; that is, treat it 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.

One final caveat: It is pointless to deny that such a theory is possible; as a purely mathematical theory, quantum information theory is not only possible, but actual, and it is quite analogous to (though not as well developed as) its cousin, classical information theory, which is also a branch of pure mathematics. The question, then, is not whether quantum theory *can* be treated purely information-theoretically, but whether it *ought* to be, for foundational purposes.

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, and so on) 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.

References

Aharonov, Y. and Kaufherr, M. (1988). Quantum frames of reference. *Physical Review D* **30**, 111–112.

Barbour, J. B. (1989). *The Discovery of Dynamics: A Study from a Machian Point of View of the Discovery and the Structure of Dynamical Theories.* Oxford: Oxford University Press.

Bohm, D. (1951). *Quantum Theory* Prentice-Hall.

Busch, P., Grabowski, M., and Lahti, P. (1995). *Operational Quantum Physics.* Berlin: Springer-Verlag.

Clifton, R., Bub, J., and Halvorson, H. (2003). Characterizing quantum theory in terms of information-theoretic constraints. *Foundations of Physics* **33**, 1561–1591.

Dickson, M. (2004). The view from nowhere: quantum reference frames and quantum uncertainty. *Studies in History and Philosophy of Modern Physics* **35**, 195–220.

DiSalle, R. (1991). Conventionalism and the origins of the inertial frame concept. *PSA 1990.* The Philosophy of Science Association, East Lansing.

DiSalle, R. (2002). Space and Time: Inertial Frames. In E. N. Zalta (ed.), *The Stanford Encyclopedia of Philosophy.* http://plato.stanford.edu/archives/sum2002/entries/spacetime-iframes.

Fuchs, C. A. (2003). Quantum mechanics as quantum information, mostly. *Journal of Modern Optics*, **50**, 987–1023.

Halvorson, H. (2004). Complementarity of representations in quantum mechanics. *Studies in History and Philosophy of Modern Physics* **35**, 45–56.

Joos, E. and Zeh, H. D. (1985). The emergence of classical properties through interaction with the environment. *Zeitschrift für Physik* **B 59**, 223–243.

Leggett, A. J. (1984). Schrödinger's cat and her laboratory cousins. *Contemporary Physics* **25**, 583–594.

Mackey, G.W. (1949). Imprimitivity for representations of locally compact groups. *Proceedings of the National Academy of Sciences U.S.A.* **35**, 156–162.

Mackey, G.W. (1978). *Unitary group representations in physics probability and number theory*, *Math Lecture Notes Series*, Vol. 55. Menlo Park, CA: Benjamin Commings Publishing Company.

Mackey, G.W. (1996). The relationship between classical mechanics and quantum mechanics. In ed. L.A. Coburn and M.A. Rieffel (eds.), *Perspectives on Quantization.* Providence, RI: American Mathematical Society.

Nielsen, M. A. and Chuang, I. L. (2000). *Quantum Computation and Quantum Information.* Cambridge: Cambridge University Press.

Raussendorf, R. and Briegel, H. J. (2001). A one-way quantum computer. *Physical Review Letters* **86**, 5188–5191.

Raussendorf, R., Brown, D. E. and Briegel, H. J. (2003). Measurement-based quantum computation on cluster states. *Physical Review A*, **68**, 022312.

Varadarajan, V.S. (1985). *Geometry of Quantum Theory.* Berlin: Springer-Verlag.

Zurek, W. H. (1982). Environment-induced superselection rules. *Physical Review D* **26**, 1862–1880.