Explaining Information Transfer in Quantum Teleportation

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In this paper I introduce a new species of teleportation which I use to evaluate three explanations of information transfer in quantum teleportation. I will argue that two explanations fail to explain the "physical effect" of teleportation. I will also argue that that information transfer, understood as something more than simple qubit transfer, is not necessary for teleportation to occur.

1. Introduction. Quantum teleportation is a recently discovered phenomenon by which it is possible to transfer the quantum state of one particle to another. This can be done without knowing the state that is transferred and, seemingly, without a direct interaction between the two particles. Teleportation has come to play an extremely important role in the field of quantum computation. In particular, it is used to send quantum information from one spatial location to another while minimizing noise (i.e., without decoherence).

The fundamental unit of quantum information is a qubit. A qubit can be physically realized by any two state system such as photon polarization or spin of an electron (Deutsch and Hayden 1999, 2). A qubit can store one classical bit of information. If an observer knows which observable that bit is stored in, a measurement of that observable will reveal the classical bit of information (Deutsch and Hayden 1999, 2). In contrast to a classical bit, the description of a qubit requires an infinite amount of information. The amount of information is infinite because two real num-

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bers are required in the expansion of the state vector of a two state quantum system (Jozsa 1997, 1).

Quantum teleportation was originally touted as a curious instance of how a qubit can be transferred from one location A to another location B without physically moving a qubit from A to B or without information flow (Bennett et al. 1993). Some explanations of teleportation have surfaced. Some have focused on explaining why only two classical bits are sufficient to teleport a qubit, even though it takes an infinite amount of information to specify a qubit. Others have focused on explaining how information is transferred during teleportation. Minimally, all responses are concerned to elucidate how a qubit gets from some point A to some point B as a result of teleportation. In this paper I will review some elementary results about quantum teleportation and then evaluate four explanations of information transfer in teleportation. I will evaluate explanations in two respects. I will first evaluate them as explanations of how a qubit gets from some point A to some point B as a result of teleportation. I will then evaluate the role that information transfer plays in the explanations. In doing so, it will become clear that three different concepts of quantum information are used in the explanations. I will argue that in all cases, information transfer, understood as anything more than qubit transfer, is unnecessary for teleportation to occur.

2. Teleportation. In order to understand where existing explanations go wrong, it is necessary to understand the quantum theoretical treatment of teleportation. The following protocol I call *conventional teleportation.*

Suppose two people, Alice and Bob, are physically separated. Alice has a photon in a state unknown to her, $|\varphi_1\rangle$. To teleport, Alice and Bob make use of EPR-type entanglement and a classical telephone call.

Two photons are initially prepared in a singlet state

$$|\Psi^-_{23}\rangle = \sqrt{\frac{1}{2}}\,(\,|H_2\rangle|V_3\rangle - |V_2\rangle|H_3\rangle\,), \tag{1}$$

where H and V refer to horizontal and vertical polarization respectively. Alice is given photon 2 and Bob photon 3. The entire system, photons 1, 2, and 3, occupies the product state $|\varphi_1\rangle|\Psi^-_{23}\rangle$. We may expand the state of the first particle as

$$|\varphi_1\rangle = a|H_1\rangle + b|V_1\rangle, \tag{2}$$

where $|a|^2 + |b|^2 = 1$. The complete state of the system is then given by

$$| \Psi_{123}\rangle = a \sqrt{\frac{1}{2}} (|H_1\rangle|H_2\rangle|V_3\rangle - |H_1\rangle|V_2\rangle|H_3\rangle) + b \sqrt{\frac{1}{2}} (|V_1\rangle|H_2\rangle|V_3\rangle - |V_1\rangle|V_2\rangle|H_3\rangle). \quad (3)$$

(3) can be further expanded using the Bell operator basis vectors $|\Psi^{\pm}{}_{12}\rangle$ and $|\Phi^{\pm}{}_{12}\rangle$ as

$$| \Psi_{123}\rangle = \frac{1}{2} [|\Psi^{-}{}_{12}\rangle(-a |H_3\rangle - b |V_3\rangle) + |\Psi^{+}{}_{12}\rangle(-a |H_3\rangle + b |V_3\rangle) + |\Phi^{-}{}_{12}\rangle(a |V_3\rangle + b |H_3\rangle) + |\Phi^{+}{}_{12}\rangle(a |V_3\rangle - b |H_3\rangle)], \quad (4)$$

where

$$|\Psi^{\pm}{}_{12}\rangle = \sqrt{\frac{1}{2}}(|H_1\rangle|V_2\rangle \pm |V_1\rangle|H_2\rangle) \text{ and}$$
$$|\Phi^{\pm}{}_{12}\rangle = \sqrt{\frac{1}{2}}(|H_1\rangle|H_2\rangle \pm |V_1\rangle|V_2\rangle). \quad (5)$$

In order to teleport $|\varphi_1\rangle$, Alice measures the Bell operator, whose eigenvectors are listed in (5). In the language of orthodox quantum theory she projects the system into a tensor product of one of those states and a state $|\varphi_3\rangle$, which is either

$$(-a |H_3\rangle - b |V_3\rangle)_1, (-a |H_3\rangle + b |V_3\rangle)_2, (a |V_3\rangle + b |H_3\rangle)_3, \text{ or } (a |V_3\rangle - b |H_3\rangle)_4. \quad (6)$$

We represent which of the above states photon 3 possesses by $|\varphi_3\rangle_i$, where i refers to the above subscripts. Photon 3 is now only a unitary transformation away from the state $|\varphi_1\rangle$. The transformations that need to be applied are contained in the following equations:

$$a |H_3\rangle + b |V_3\rangle = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} |\varphi_3\rangle_1, \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} |\varphi_3\rangle_2, \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} |\varphi_3\rangle_3, \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} |\varphi_3\rangle_4, \quad (7)$$

where the above unitary matrices are defined relative to the basis:

$$|H\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \text{ and } |V\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}.$$

In the case of $|\varphi_3\rangle_1$, photon 3 differs from $|\varphi_1\rangle$ by an irrelevant phase factor and no transformation need be applied. The other possible states are unitary transformations away from the original state of Alice's photon. In order to complete the teleportation process, Alice must tell Bob the appropriate transformation to perform on his photon based on the outcome of her Bell operator measurement, or BOM for short.

For instance, if Alice obtains the $|\Phi^{+}{}_{12}\rangle$ outcome, Bob will apply the

$$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

transformation to teleport. After Bob performs the required transformation, his photon will be in the initial state $|\varphi_1\rangle$. Assuming Alice and Bob prearrange a numbering system for each one of the four possible unitary transformations to apply for successful teleportation, Alice only has to communicate a number between 1 and 4 to Bob. Two bits are sufficient to do this.

3. Teleportation without Phone Bills. Successful teleportation depends on three things. 1. Alice and Bob each need to receive one member of a pair of entangled photons. 2. Alice needs to perform a BOM on her two photons. 3. Bob must perform the appropriate transformation on his photon. An unknown quantum state has been transferred from one system to another when all three have been completed. The telephone call from Alice to Bob is absent from the above list and I will argue it is *dispensable* to the physical component of teleportation.

By "physical component" of teleportation I mean that Bob has the unknown state in his possession or measurement results that reflect the statistics of the unknown state, and that the conditions 1., 2., and 3. have been satisfied. By discussing the physical component of teleportation I wish to contrast it with *knowledge* of successful teleportation. I will argue that the telephone call changes Bob's knowledge rather than anything physical.

Suppose conditions 1., 2., and 3., have been satisfied. Call the unitary transformation Bob performed on his photon U. Bob will assign a density operator that describes an equal weighted mixture of the pure states $U|\varphi_3\rangle_i$, where $i = 1, \ldots, 4$, to his photon; however, the state of his photon is actually in one of the pure states of the mixture. If Alice calls Bob and tells him which unitary transformation to perform based on the results of her BOM, Bob will then conditionalize on this new knowledge and assign one of the pure states $U|\varphi_3\rangle_i$ to his photon. If we suppose that Bob had inadvertently performed the correct unitary transformation, the state of his photon will be such that $|\varphi_3\rangle = |\varphi_1\rangle$ before he receives a call from Alice, even though his density operator will describe an equal mixture of pure states. Thus, the physical component of teleportation can occur without Bob knowing which pure state he has.

4. Backwards Teleportation. Once it is realized that a phone call is unnecessary for the physical component of teleportation, it can be shown that the time order of operations 2. and 3. in the teleportation protocol is also irrelevant to the physical component of teleportation. In fact, Bob can even make a measurement on his member of the EPR pair before Alice performs the BOM. Even in this case Alice will be able to use the results of her BOM to know if $|\varphi_3\rangle = |\varphi_1\rangle$. Or, if several teleportation attempts are made, Alice will be able to pick out a subensemble of Bob's photons that are in the state $|\varphi_1\rangle$ or measurement results that reflect the appropriate statistics for $|\varphi_1\rangle$. The statistics for that subensemble will be the same as those that would have been found using the conventional teleportation scheme. The following simple example will make this clear.

Consider only the cases in which Bob performs no transformation on his photon, always measures vertical polarization, and does these things in the timelike past of Alice performing her BOM. What we want to know is the probability that Bob's photon has vertical polarization given that Alice measured the $|\Psi^-_{12}\rangle$ outcome, $\mathrm{Prob}(|V_3\rangle / |\Psi^-_{12}\rangle)$. When Alice gets the $|\Psi^-_{12}\rangle$ outcome for her BOM Bob does not need to perform a transformation. The conditional probability is simply

$$\mathrm{Prob}(|V_3\rangle \,/\, |\Psi^-_{12}\rangle) = \frac{|P_{|\Psi^-_{12}\rangle} P_{|V_3\rangle} |\Psi_{123}\rangle|^2}{|P_{|\Psi^-_{12}\rangle} |\Psi_{123}\rangle|^2}, \tag{8}$$

where $P|\varphi\rangle$ is the projection operator for a state $|\varphi\rangle$. Using equation (4) and (8) we have

$$\mathrm{Prob}(|V_3\rangle \,/\, |\Psi^-_{12}\rangle) = |b|^2 \tag{9}$$

and this is exactly the probability we would expect when the state $|\varphi_1\rangle = a|H_1\rangle + b|V_1\rangle$ has been teleported. It is no mystery why these correlations exist even when Bob performs his transformations and measurements before Alice does. $P|\Psi^-_{12}\rangle$ and $P|V_3\rangle$ commute, so the time order of the operations to which these projectors correspond makes no difference to the conditional probability. Thus, the physical component of teleportation occurs in this rather backwards protocol. In what follows, I will refer to the teleportation protocol in which there is no phone call from Alice and Bob's transformation occurs in the timelike future of Alice's BOM as *scaled back teleportation*. I will refer to the teleportation protocol in which there is no phone call from Alice and Bob's transformation occurs in the timelike past of Alice's BOM as *backwards teleportation*.

Should we consider backwards teleportation an actual instance of teleportation? I think the answer is yes. First we must recognize that the physical processes necessary for scaled back teleportation are the same as those for conventional teleportation, as I've argued above. Next is to argue that the same relation holds between scaled back and backwards teleportation. The "raw materials" for teleportation are the same in both cases: entangled photons, BOM, unknown state, unitary transformations, and polarization measurements. The only difference between scaled back and backwards teleportation is the time order of events. If there is any difference in the physical processes responsible for teleportation in the two cases, it must be because of the difference in the time order of events. However, the formalism of quantum theory picks out no privileged time order for the operations performed by Alice and Bob. The projection operators corresponding to the difference in order of events for scaled back and backwards teleportation commute. Minimally this indicates that the order of operations will have no statistical effect on the outcomes of measurements. Thus, it is unlikely that there are two distinct physical processes that distinguish scaled back and backwards teleportation. This fact will be useful in critiquing explanations of information transfer in teleportation.

5. Explaining Information Transfer in Quantum Teleportation. Explanation in general is a notoriously difficult topic in philosophy of science. Explanation as it applies to quantum mechanics is even more difficult. Nonetheless, several types of explanation have been employed in the quantum domain to help us better understand the world. Two have enjoyed much popularity.

The most basic type of explanation available for quantum phenomena is something akin to Hempel's D-N model of explanation. Hempel regards an explanation as a deductive argument whose premises state laws of nature and initial conditions and whose conclusion describes the explanandum. On this view, a quantum theoretic derivation of a phenomenon would underwrite the explanation of that phenomenon. Most philosophers are unsatisfied with this type of explanation. The criticism often raised against this type of explanation is that it fails to increase our understanding of the world. To supplement this type of explanation an interpretational framework is often employed.

Interpretations of quantum theory give some account of the way the world is or works that is consistent with quantum mechanical formalism. Examples of interpretations include the Many Worlds Interpretation, quantum holism, the Copenhagen Interpretation, modal interpretation, etc. An explanation of a quantum phenomenon is given by showing how the phenomenon naturally follows from the kind of world the interpretation assumes plus the quantum theoretical formalism.

The first two explanations of information transfer in quantum teleportation I will consider are of the latter type. The third explanation I consider is of the first type. In what follows, I will apply each of those three types of explanations to scaled back and backwards teleportation in the attempt to understand the relationship between the physical component of teleportation and information transfer. I will argue that information transfer, understood as anything more than simply as the transfer of a qubit from Alice to Bob, is not necessary for the physical component of teleportation. I will also argue that the first two explanations, those that go beyond the quantum formalism, fail to explain backwards teleportation and hence the physical component of teleportation.

The authors of the original teleportation paper inferred that since an infinite amount of information is required to specify a qubit, an infinite amount of information, as some ontologically robust entity, has to be transferred to teleport a qubit (Bennett et al. 1993).[1] Thus, they offered a possible mechanism for information transfer to explain teleportation. They suggested operation 2. disassembles a qubit into classical and quantum information. Bob's photon receives quantum information from Alice's photon via the nonlocal EPR channel they share. The remaining information is sent via a classical channel to Bob, which enables him to reconstruct the qubit.

This interpretation can explain the success of backwards teleportation. After the BOM all but two bits of classical information have been transferred to Bob's qubit. Bob can accidentally provide the correct two bits of information such that teleportation is successful.

It is unlikely that there exists a nonlocal EPR channel by which information is transferred during teleportation. According to the Bennett et al. interpretation, in the case of backwards teleportation, there is no channel open to Bob's photon to receive information about the state Alice wants to teleport. In backwards teleportation Bob performs a measurement on his member of the EPR pair before Alice's member interacts with the state to be teleported. On the assumption that information cannot be transferred back in time, this eliminates any possible channel for information transfer from Alice's photon to Bob's. Nonetheless, the physical component of teleportation occurs. Thus, it appears that on Bennett et al.'s account of information, no information transfer is required for the physical component of teleportation. Since it is information which does all the explanatory work in Bennett et al.'s account of teleportation, their explanation of the physical component of teleportation is unsatisfactory.

Lev Vaidman finds it paradoxical that only two bits of information are sufficient for teleportation when a qubit requires an infinite amount of information to specify. Vaidman explains why two bits are sufficient based on the structure of the world dictated by his version of the Many Worlds Interpretation (MWI). He suggests that the quantum state of the particle to be teleported, Ψ, is in some sense located in Bob's particle from the

1. Bennett et al. do not explicitly spell out their concept of information. This prevents me from saying more about "ontologically robust entities."

beginning. The correlated pair "incorporates all possible quantum states of the remote particle, and, in particular, the state Ψ which has to be teleported" (Vaidman 1994, 216). Vaidman's task is to show how the conventional teleportation protocol allows the state Ψ to manifest itself in Bob's member of the EPR pair. According to the MWI, Alice's BOM splits the world into four. The state of Bob's particle in each of these worlds is a unitary transformation away from the state Ψ. Two bits are required to indicate which world Bob is in, which in turn indicates which transformation to perform for successful teleportation. Hence, conventional teleportation is explained.

The MWI also makes sense of scaled back teleportation. The success of scaled back teleportation is explained by the fact that Bob can correctly guess which world he is in 25% of the time and perform the correct transformation to put his particle in state Ψ. It is clear that on Vaidman's account, no information transfer via two bits is required for the physical component of teleportation. The MWI does not fare well when we try to explain backwards teleportation.

The backwards teleportation scheme in the language of the MWI is this: When Bob makes a measurement on his photon, say vertical polarization, two possibilities exist. In one world Bob's photon will pass, in another it will be absorbed. In both worlds, the state of Alice's two particles will be in a superposition of the Bell operator basis vectors. A BOM in both worlds will split each world up four ways. The structure of the worlds in this case does not indicate any illuminating relationship between the results of the BOM and Bob's measurements. However, that is what is required of the MWI to explain Alice's ability to pick out an ensemble of Bob's measurements that reflect the statistics for the state Ψ. Hence, Vaidman's MWI fails to provide an explanation of the physical component of teleportation.

Recently, Deutsch and Hayden (1999) have given what they claim is a purely local account of information transfer in teleportation. Deutsch and Hayden demonstrate how, contrary to appearances, all information required to specify a qubit is transferred to Bob in the two classical bits he receives in the telephone call. Deutsch and Hayden perform their analysis using a modified version of the Heisenberg picture on a quantum computational network. The advantage of using this picture is that it makes explicit the location of information in quantum systems at each stage of the teleportation protocol.

It is not necessary to recapitulate the details of Deutsch and Hayden's analysis to understand how they arrived at their conclusion; however, a basic understanding of their picture is essential. In contrast to the conventional Schrödinger picture, where operators are constant and the state vector of a system evolves with time, the Heisenberg picture is just the opposite: operators evolve in time and the state vector of a system is constant. Thus, in the Heisenberg picture, the observable properties of a system are a function of the time evolution of the operators for the observables.

As remarked earlier, the location of information in a quantum system can be made explicit in the Heisenberg picture. Deutsch and Hayden have a sufficient condition for a system to contain information: "We require only that a system S be deemed to contain information about a parameter θ if (though not necessarily only if) the probability of some outcome of some measurement on S alone depends on θ"(Deutsch and Hayden 1999, 3). A simple example demonstrates the location of information in a quantum system. Consider an EPR pair initially in the state $|\Psi\rangle = i\sqrt{\frac{1}{2}}(|0\rangle_1|0\rangle_2 - |1\rangle_1|1\rangle_2)$. Suppose that particle 1 is rotated through an angle θ. The system is now in the state:

$$|\Psi\rangle = \sqrt{\frac{1}{2}}[\sin(\theta/2)(|1\rangle_1|0\rangle_2 - |0\rangle_1|1\rangle_2) + i\cos(\theta/2)(|0\rangle_1|0\rangle_2 - |1\rangle_1|1\rangle_2)]. \quad (10)$$

Note that in this picture, the state $|\Psi\rangle$ is identical to one in which the same transformation was performed on particle 2 instead of particle 1. Thus, it is unclear where the information about the angle of transformation resides: particle 1 or particle 2. In the Heisenberg picture it *is* clear where the information resides. The state of the EPR system after the transformation in the Heisenberg picture is given by the descriptors of each particle:

$$\begin{aligned} q_1 &= (\sigma_x \otimes \mathbf{1}, -(\cos(\theta)\sigma_y + \sin(\theta)\sigma_z) \otimes \sigma_x, (\sin(\theta)\sigma_y - \cos(\theta)\sigma_z) \otimes \sigma_x,) \\ q_2 &= (\sigma_x \otimes \sigma_z, -\sigma_x \otimes \sigma_y, 1 \otimes \sigma_x) \end{aligned} \quad (11)$$

where q_a is the descriptor of the a^{th} qubit, $\mathbf{1}$ is the identity and the σ_i's are Pauli spin matrices (Deutsch and Hayden 1999, 19). Only the first particle depends on the angle of transformation. Thus, in the Heisenberg picture the location of information is explicit. Using this feature of the Heisenberg picture, Deutsch and Hayden demonstrate how information about $|\varphi_1\rangle$ gets to Bob.

Deutsch and Hayden's teleportation protocol uses 5 qubits. All qubits begin the computation in the same state. Qubit 1 is the qubit to be teleported. It is subjected to a rotation θ about the x axis to prepare an "unknown" state. Deutsch and Hayden will analyze how information about θ gets from Alice to Bob. The EPR channel between Alice and Bob is prepared by an operation Bell^{-1} which fully entangles qubits 4 and 5. Qubit 5 is sent to Bob and qubit 4 is sent to Alice. Like the conventional teleportation protocol, Alice will perform a BOM on qubits 1 and 4. The result of this measurement is recorded in qubits 2 and 3 by two operations called cnot. The telephone call between Alice and Bob is represented by the qubits 2 and 3 traveling from Alice to Bob. At Bob, qubits 2, 3, and 5 are subjected to an operation called T. This operation performs a particular transformation to qubit 5 based on the binary number stored in qubits 2 and 3. Figure 1 summarizes the procedure.

Much like equation (11), it is clear in the Heisenberg picture of the system that information about the rotation to which qubit 1 was subjected is stored in qubits 2 and 3. The Heisenberg state of qubits 2 and 3 at t = 3, the time when information about the result of Alice's BOM is stored in qubits 2 and 3 is:

$$q_2(3) = (\mathbf{1} \otimes \sigma_x \otimes \mathbf{1}^3, (\sin(\theta)\sigma_y - \cos(\theta)\sigma_z) \otimes \sigma_y \otimes \mathbf{1} \otimes \sigma_z \otimes \sigma_x, (\sin(\theta)\sigma_y - \cos(\theta)\sigma_z) \otimes \sigma_z \otimes \mathbf{1} \otimes \sigma_z \otimes \sigma_x) \quad (12)$$
$$q_3(3) = (\mathbf{1}^2 \otimes \sigma_x \otimes \mathbf{1}^2, -\sigma_x \otimes \mathbf{1} \otimes \sigma_y \otimes \sigma_x \otimes \mathbf{1}, -\sigma_x \otimes \mathbf{1} \otimes \sigma_z \otimes \sigma_x \otimes \mathbf{1})$$

where $\mathbf{1}^n$ denotes the tensor product of n copies of the unit matrix and the number in parenthesis is the time index for the qubit (Deutsch and Hayden 1999, 15). As one can see, information about the transformation performed on Alice's particle is present in qubit 2. Deutsch and Hayden comment on why the θ term is absent in qubit 3:

> The fact that in this simplified example the information about θ at t = 2 is absent from Q4 [qubit 4], and that it is then (t ≥3) carried only in Q2 and not in Q3, has no fundamental significance: had we

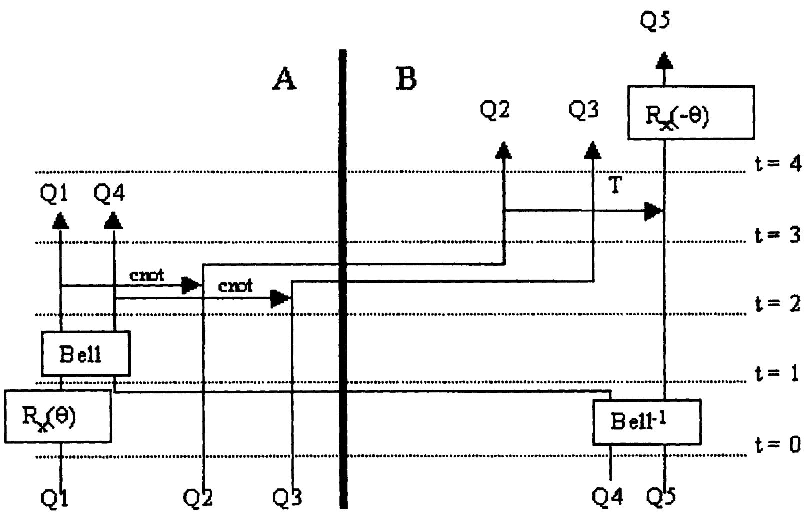

Figure 1. Deutsch and Hayden's teleportation experiment.

> been teleporting a general pure state, which would require us to choose two real parameters at A instead of one, . . . [qubits 2 and 3] . . . would all generically depend on both those parameters, and both Q2 and Q3 would be needed to transport the information about our choice to B. (Deutsch and Hayden 1999, 15)

Thus, all information required to specify a qubit is physically carried from Alice to Bob.

The information stored in the two qubits sent from Alice to Bob is of a special type. It is what Deutsch and Hayden call *locally inaccessible* information. Locally inaccessible information is defined as "information which is present in a system but does not affect the probability of any outcome of any possible measurement on that system alone" (Deutsch and Hayden 1999, 12). There is no measurement that can be performed on the two qubits alone such that the probability of any possible outcome will depend on θ. That is why prior to this analysis the classical channel was not considered to convey any information besides a binary number. The information in qubits 2 and 3 is only accessible when qubits 2 and 3 interact with qubit 5. As such, Deutsch and Hayden interpret entanglement as a key which allows access to the information stored in qubits 2 and 3.

> Thus, in our teleportation experiment, the inverse Bell operation at $t = 0$ sets up the algebraic relationships between . . . [Q4 and Q5]. These relationships constitute quantum information that is not locally accessible in either Q4 or Q5, and is the key that is copied into Q2 and Q3 by the measurements at $t = 2$, and then allows Q5 to recover the quantum information about θ that is hidden in Q2 and Q3. (Deutsch and Hayden 1999, 18)

Deutsch and Hayden's explanation of information transfer in quantum teleportation differs from the previous three discussed above. Contrary to those explanations, Deutsch and Hayden seem to have good formal reasons for suggesting that information transfer, considered as something beyond transfer of a qubit from Alice to Bob, takes place during conventional teleportation. The parameter θ is contained in the descriptors for the classical channel between Alice and Bob. However, since they claim that the two classical bits transferred from Alice to Bob contain all the information about $q_1(1)$, they would have to conclude that information is not transferred in the case of scaled back or backwards teleportation. Thus, on Deutsch and Hayden's analysis we must conclude that information transfer is unnecessary for the physical component of teleportation to occur. Deutsch and Hayden neglect to give an explanation of the physical component of teleportation beyond the formalism, and hence a critique is not warranted. It is tempting to suppose that the reason teleportation is possible is that the classical channel physically provides the transfer of the information that constitutes Alice's qubit to Bob's qubit. Such a suggestion is unreasonable because the physical component of teleportation occurs without information transfer in the above mentioned way.

6. Conclusion. We have examined several explanations of information transfer in quantum teleportation. Some have differing explanatory agendas. This occurs because there are a number of loosely defined concepts of quantum information at play in the literature and it is unclear exactly what should be explained about information transfer during quantum teleportation.

We have encountered the following concepts of information in the above explanations: 1. information required to specify a qubit; 2. ontologically robust information that constitutes a qubit; 3. Deutsch and Hayden's concepts of locally accessible/inaccessible information. The distinction between concepts 1. and 2. is essential. Vaidman uses concept 1. rhetorically to motivate a paradox regarding why two bits are sufficient for teleportation. His actual explanation seems to focus more on how teleportation is possible in his interpretational framework rather than focusing specifically on information transfer in teleportation.

Concept 2. is used by Bennett et al. Recall that they infer that since an infinite amount of information is required to specify a qubit, an infinite amount of information must be transferred to teleport. Thus, their explanatory project is to provide a mechanism whereby all the information required to specify a qubit is actually transferred. There seems to be no reason to make the inference that motivates this explanatory project. In fact, there is reason to doubt that it is a good one to make. If it were true that information actually had to be transferred, backwards teleportation should not be possible. Recall that there seems to be no possible mechanism for information transfer in backwards teleportation. Backwards teleportation is possible, so it seems that the inference made by Bennett et al. is not a good one to make.

Deutsch and Hayden seriously take up the project of explaining information transfer in quantum teleportation. They employ a well defined concept of information in their analysis of teleportation that fits well into quantum theoretical formalism. The location of information can be read off directly from the formalism without appeal to any extra-theoretical entities.

As we have seen, several concepts of quantum information have been used in the above explanations. Different concepts of information motivated different accounts of information transfer in teleportation. Thus, there is no consensus on what exactly needs to be explained. Two projects can be coerced out of the above discussion. The first is explaining the physical component of teleportation. It seems that the first two explanations examined share this goal to a large extent. Both fail to explain the physical component of teleportation. It is clear from the above discussion that information, whatever it is, plays no role in accounting for the physical component of teleportation. The second explanatory project is explaining information transfer during teleportation. This is the task that Deutsch and Hayden take up successfully. I would like to suggest the type of explanation they offer is exactly the type of explanation that is required for information transfer in quantum teleportation. Explanations that go beyond the formalism often introduce unnecessary metaphysical baggage that, as we have seen, lends nothing to, and often obscures, the explanatory project.

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