# ABSTRACT


Title of dissertation: Deutsch's CTC Model and its Implications for the Foundations of Quantum Theory

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This dissertation is an exploration of several issues surrounding David Deutsch's CTC model first introduced in his 1991 paper "Quantum Mechanics Near Closed Timelike Lines" [1]. Deutsch developed his model to account for the effects of quantum theory, which had been left out of classical discussions of time travel paradoxes. Deutsch's formulation of his model in terms of quantum computational circuits lends itself to being adopted in the quantum information community.

The dissertation argues that the adoption of the D-CTC model entails the existence of Nonlocal Signaling, which is in conflict with a fundamental principle of the quantum information approach. In order to motivate this argument, in Chapter 2 I introduce a distinction between Nonlocal Signaling, and Superluminal Information Transfer. In the latter case, a carrier of information physically traverses the space between the distant communicating parties faster than the speed of light. Exploiting quantum entanglement to signal, however, need not have this feature. I term this Nonlocal Signaling. Chapter 3 is where I present the argument that D-CTCs entail Nonlocal Signaling, and examine the controversy surrounding this and related

results. I argue that the resistance to these kinds of predictions in the literature is motivated by a commitment to the principles of quantum information theory, which are inappropriately applied here.

Chapters 4 and 5 examine details of Deutsch's model. Chapter 4 argues that it presupposes a significant metaphysical picture that, when explicitly stated, makes a much less comfortable fit between D-CTCs and quantum information theory. Chapter 5 argues that, because of Deutsch's commitment to this metaphysical picture, he is committed to the existence of physical situations that are in every way indistinguishable from the paradoxes he attempts to rule out by adopting the model in the first place.

In Chapter 6, I make some observations about the relationship between the quantum information-theoretic approach to the interpretation of quantum theory, and the approaches focused primarily on arguing for one or another underlying ontology. Deutsch's model is situated squarely in the latter camp. It serves as a useful example in pulling apart the implications of the two approaches.

In conclusion, I argue that the quantum information-theoretic interpretation of quantum theory, in denying the fundamentality of any particular ontology, in favor of kinematical principles, is in tension with the metaphysical commitments of the Deutsch model. Deutsch's interpretational stance is among the metaphysically–motivated positions. I argue that this element of the Deutsch model is essential to the solutions it offers to the paradoxes of time travel, and therefore the D-CTC model cannot be adopted without implicitly endorsing Deutsch's metaphysical commitments. This feature makes the D-CTC model an uncomfortable fit with QIT.

# Deutsch's CTC Model

## and its Implications for the Foundations of Quantum Theory

by

Lucas Dunlap

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# Dedication

Dedicated to Meliss, of course.

# Acknowledgments

I am in the very lucky position to acknowledge the great help I have received over the last several years in my study of the foundational issues at the heart of quantum theory. Jeffrey Bub and Allen Stairs have contributed in no small part to my understanding, however humble it may be. They have given me guidance on matters intellectual and professional, and I owe them both a great debt. My appreciation of the philosophical issues in the sciences has been enriched by study and discussion with Lindley Darden, Mathias Frisch, James Mattingly, Wayne Myrvold, Eric Pacuit, Aidan Lyon, David Albert, Lane DesAutels, Melissa Jacquart, Max Bialek, J. Brendan Ritchie, Michael Jarret, and Prabal Adhikari. The rest of the wonderful philosophy department here at Maryland has my thanks, as well. And special thanks go to Louise Gilman, who is both the brains and the heart of our department.

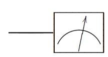
On a more personal note, I would like to acknowledge the support of my parents, who have never dissuaded me from pursuing my strange interests. A philosophy doctorate in the metaphysical considerations raised by quantum computers with access to time-traveling qubits is a testament to their tolerance and encouragement.

My timely completion of this project would not have been possible without the financial support of the University of Maryland Department of Philosophy in the form of teaching assignments, summer research fellowships, travel funds, and the Moreland Perkins Fellowship in Philosophy. The Graduate School was also kind enough to provide me with funds in the form of the Graduate School Travel Award, and the Goldhaber Travel Award. The Rotman Institute of Philosophy at Western University was kind enough to host me for a semester as a visiting research student. Special thanks go to Carl Hoefer, Wayne Myrvold, and Stathis Psillos. That visit was made possible by the support of the National Science Foundation Doctoral Dissertation Research Improvement Grant, award number 1431229.

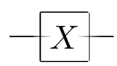
# Table of Contents

# Abbreviations and Diagrams

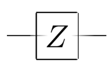
| | |
|---|---|
| CTC | Closed Timelike Curve |
| D-CTC | Deutsch's Closed Timelike Curve model |
| P-CTC | The "Projective" or "Post-Selected" Closed Timelike Curve model |
| CR | Chronology–Respecting (referring to a region not containing a CTC) |
| MWI | Many–Worlds/Everett Interpretation of quantum mechanics |
| QIT | Quantum Information Theory |
| BHW | Brun–Harrington–Wilde circuit for distinguishing BB84 states. |
| BB84 | The set of four non-orthogonal states $\vert 0\rangle$, $\vert 1\rangle$, $\vert +\rangle$, and $\vert -\rangle$ |
| QITI | Quantum Information–Theoretic Interpretation of quantum mechanics |
| MWM | Many–Worlds Multiverse |
| MSM | Mixed State Multiverse |
| CCC | Classical Consistency Condition |
| GR | The General Theory of Relativity |
| SR | The Special Theory of Relativity |
| PO | The Primitive Ontology framework |
| DC | Direct Causal Model |
| CC | Common Causal Model |
| SD | Signaling Device |

Measurement  Projection onto measurement basis $\{|0\rangle, |1\rangle\}$

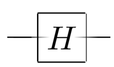
*NOT* or *X* 

$=$ 

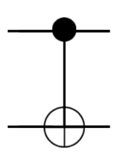
$= \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$

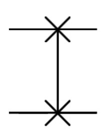
*Z* 

$= \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$

Hadamard 

$= \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

*CNOT*  $= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$

*SWAP*  $= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

# Chapter 1: Introduction

## 1.1 Background

### 1.1.1 General

The theoretical exploration of the power of quantum systems to supplement the information–transmission and –processing capabilities of classical communication and computation systems provides a powerful insight into the strange characteristics of the quantum world. The possibility of encoding information in physical systems that are not constrained to the two values—on and off, one and zero—of the classical bit allows for nonclassical processes and transformations that can implement quantum computational algorithms, some of which are known to offer an exponential speed–up over their fastest–known classical counterparts. As far as we know, quantum physics offers information processing resources that go above and beyond those allowed in classical information theory and computer science.

The Quantum Information Theory research program (QIT) has led to important breakthroughs in our understanding of how quantum mechanics extends our ability to encode, encrypt, send, and process information. It allows us to explore what we can *do* in a quantum world. However, what it tells us about the *nature* of the quantum world is less clear.

The correct interpretation of quantum theory is a subject of much debate. Quantum physics has a serious foundational problem—a problem with the self-consistency, or "stability" of the theory—called the *measurement problem*. Different proposed solutions to this problem yield different interpretations with different commitments with respect to what kinds of entities the theory posits as existing at the most fundamental level.

QIT represents an alternative approach to that of the more metaphysically–invested interpretations. The QIT approach to the foundations of quantum theory involves identifying information–theoretic constraints that characterize a theory that picks out the possible states that can obtain in our world. According to QIT, these principles represent the fundamental truths about the structure of the world.

While this distinction will not be the main focus of this dissertation, it plays an important role in understanding the tension inherent in the model around which this work is based. The papers collected here focus on various aspects of David Deutsch's model for the behavior of quantum systems in the presence of closed timelike curves (the D-CTC model).

A CTC is a trajectory through spacetime along which a system could travel, that would lead it into its own past, allowing it to interact with a younger version of itself. The general theory of relativity (GR) does not rule out the possibility of CTCs. Their existence is consistent with the mathematical constraints on the geometry of spacetime imposed by the theory. This fact was first pointed out to Einstein (to his great surprise) by Kurt Gödel in 1949 [2] [3]. Since that time, several mathematically consistent models for CTCs have been developed (see [4] [5] [6]).

The debate about the physical possibility of, and physical constraints on, these spacetime structures has taken place largely in the context of GR, rarely taking quantum mechanics into account (see [7] for a notable exception). Deutsch's 1991 "Quantum Mechanics Near Closed Timelike Lines" represents the genesis of a different approach to analyzing CTCs [1]. Rather than engaging in the debate about the extent to which GR allows CTCs, Deutsch asked the following question: Assuming we had access to reliable CTCs, what can we do with them?

David Deutsch had already established himself a chief founding figure in the QIT approach and in quantum computation.[1] The approach he takes to analyzing CTCs mirrors the QIT approach to the analysis of quantum mechanics. The focus is on what can be practically achieved in a world that gives us access to these resources.

Deutsch has expressed the belief that the proper way to understand physical processes is in terms of Information Flow [10]. Our fundamental analyses of the evolutions and interactions of physical systems should be in terms of the manipulation and exchange of information. It was only natural, then, that Deutsch's attempt to answer the question of the power of CTCs was formulated in terms of computation and information transmission.

Most importantly, however, the move away from the GR regime was motivated by what Deutsch saw as a major failing of all previous analyses of CTCs: They ignored the fact that quantum mechanics allows systems to exist in states that are

[1]For example, he developed the first quantum computational algorithm which demonstrated a significant speed–up over any classical counterpart. [8] [9]

classically impossible.[2]

In particular, Deutsch was interested in the power of quantum mechanics to solve the paradoxes of time travel. All previous attempts to solve the two major time travel paradoxes—the Grandfather Paradox and the Knowledge Paradox—had proceeded from the assumption that the state of the system traveling though time must be definite. Part of the power of quantum mechanics is that it allows for the existence of superposed and quantum mixed states. In the former case, the system is not in a definite state with respect to the basis of interest, but rather in some linear combination of its eigenstates. The latter case is even more general, where the system may not even be in a definite linear combination of eigenstates of the measurement basis. The important feature of these states is that the are in a sense "in between" the states allowed in classical physics.

This is relevant because the classical solutions to the paradoxes of time travel have the feature of ruling out certain initial experimental setups, since the propagation of a system in that definite state along a CTC would yield a contradiction. This feature of the classical solutions is often referred to as *superdeterminism*, since it puts constraints on the initial conditions of an experiment, that go over and above the constraints imposed by the deterministic theory itself.[3] Deutsch has expressed

[2]Even Hawking's [7], in which his argument is formulated in the semi–classical gravity regime only takes quantum effects into account in predicting the existence of certain kinds of fundamental particles on the interior of a wormhole. Quantum considerations are not applied to the possible states in which systems find themselves while traversing the CTC.

[3]"Superdeterminism" is a slight misnomer in this context, given that, in a chronology–violating region, all events are in the past of all others, and therefore *determinism* itself is difficult to define. The idea being expressed by the term, however, is clear: in a chronology–violating region, all events need to be self–consistent, meaning that certain sequences of events are ruled out, even though they would not be inconsistent with the dynamics of a chronology–respecting region.

serious discomfort with this feature of the classical solutions (among others). His D-CTC model is an attempt to show that quantum mechanics can solve the paradoxes of time travel without ruling out any initial experimental condition.

The Grandfather paradox is a physical situation in which a time–traveling system's presence in the past prevents itself from time traveling in the first place. The Knowledge Paradox is a situation where a time–traveling physical system's presence in the past is causally responsible for its having time traveled to the past in the first place. A simple example of a Grandfather Paradox is going back in time to kill yourself as a baby. If you don't survive childhood, who comes back in time to assassinate you? A simple example of a Knowledge Paradox is using the plans for a time machine given to you by your time–traveling future self to go back in time and give your past self the plans. Who designed the time machine? It seems to exist in a causal loop.

The classical consistency condition (CCC) proposed independently by David Lewis and Igor Novikov, states that the history of the world must be self–consistent. This entails that trajectories that would take physical systems to the past to enact a Grandfather Paradox are impossible, because they would lead to a physical contradiction (the baby both survives toddlerdom, and doesn't). However, CCC doesn't rule out the closed causal loop of the Knowledge Paradox. After all, being uncaused is not inconsistent. This permissiveness with respect to uncaused effects is the other major feature of CCC to which Deutsch objects.

Deutsch's analysis of CTCs is formulated in terms of quantum computational circuits. In order to be able to present the D-CTC model completely, it is necessary to introduce the basic concepts of QIT and quantum computation.

### 1.1.2 Quantum Information

Quantum Information Theory has made major advances in our understanding of quantum theory over the last several decades. There are several related research topics that fall under the "quantum information" umbrella—quantum cryptography, quantum computation, the exploitation of quantum resources for communication purposes. Although there is much variety among the kind of work being done in each of these areas, there is a common thread that unifies them: each of them is primarily concerned with the kinds of macroscopic effects that can be achieved by using a quantum system in a novel way. Quantum information scientists see these kinds of results as shedding light on the structure of the theory by highlighting its implications. In service of this focus they characterize the basic unit of analysis—the quantum state—as essentially an information-bearing entity. They name the information carried by a quantum state a *qubit*, a shortening of "quantum bit". Whereas a classical bit was either in the state "on" or "off" (represented by a 1 or a 0), the nonclassical possibilities for quantum states allow the qubit to allow for classically forbidden computation and communication protocols.

As Lloyd says

> The essential goal of quantum information science is to determine how quantum weirdness can be used to enhance the capabilities of computers and communication systems. [9]

Quantum Information Theory generalizes the concept of the *bit* from classical Information Theory. In the classical case, a bit is in one of two states—0 or 1, on or off, yes or no. There are many ways to instantiate a physical system that can carry classical information. Any system that can be in one of two distinguishable states will do the trick. Information—e.g. a string of characters forming a message—can be encoded in these physical systems.

The qubit can be in definite states analogous to the classical 0 and 1 (denoted in QIT as $|0\rangle$ and $|1\rangle$), but they can also be in weighted superpositions of those states. For example a qubit might be in the state

$$|\psi\rangle_A = \alpha\,|0\rangle + \beta\,|1\rangle$$

When a measurement is made on this system, it has a probability equal to $|\alpha|^2$ that the measurement will register the outcome $|0\rangle$, and a probability equal to $|\beta|^2$ of registering $|1\rangle$. The simplest physical systems that can serve as instantiations of qubits are the spin states of spin-1/2 particles, such as electrons. For example, spin states with respect to the $x$-direction is selected as the measurement basis, meaning that $|\uparrow_x\rangle$ and $|\downarrow_x\rangle$ are taken to represent $|0\rangle$ and $|1\rangle$. Any physical state that can obtain in the electron is a possible information state of the qubit.

In addition to superposed states, qubits can be entangled with other systems, meaning that the outcome of the measurement will be correlated with the outcome of a measurement on the entangled system. When two systems are entangled with one another, neither has a definite state of its own. It is still meaningful to talk about the probabilities of outcomes of measurements, but it is not meaningful to speak of the state of each system in isolation.

The fact that qubits can be in these quantum states allows for classically impossible protocols for encoding, encrypting, and sending messages. One such protocol, which will be relevant for the discussion in Chapter 4, is *quantum teleportation*. The two parties, Alice and Bob, share a maximally entangled pair of particles.

$$\left|\Phi^{+}\right\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B\right)$$

This is a state of perfect correlation. However far apart Alice and Bob take their halves of the entangled pair of particles, the outcomes they register when they make the same measurement will always be the same. 50% of the time they'll both get the outcome $|0\rangle$, and 50% of the time they'll both get the outcome $|1\rangle$.

Entanglement is seen in QIT as an exploitable resource. It is in fact the most significant difference between classical Information Theory and QIT. The teleportation protocol shows that entanglement can be used as a channel for quantum information. In classical Information Theory, the channels along which information can be transmitted are many and varied (including voltages in circuits, light signals in fiber optical lines, etc.). But they all share the feature of requiring that the information travel continuously from the source to the receiver. The quantum teleportation protocol seems to show that this is not the case for the transmission of quantum information. This feature of QIT will be discussed in Chapter 2.

The teleportation protocol proceeds as follows: Alice has a (potentially unknown) quantum state $|\psi\rangle$ that she wants to send to her distant partner Bob. She and Bob share the maximally entangled state $|\Phi^+\rangle$. There is a measurement that Alice can make on the joint system made up of $|\psi\rangle$ and her half of the entangled pair $|\Phi^+\rangle$ that will have the effect of breaking the entanglement she shares with Bob, and destroying the original input state $|\psi\rangle$. This joint measurement maximally entangles the two particles under Alice's control. Therefore, the outcome of this measurement encodes some information about the original state $|\psi\rangle$.

Since the same measurement performed on both halves of the entangled pair will yield the same outcomes, there is a correlation between the current state of Alice's formerly entangled partner particle, and Bob's. Therefore, there exists a simple operation Bob can perform on the system under his control that will bring it into the state $|\psi\rangle$ with which Alice originally began. Depending on the outcome of Alice's joint measurement on her two particles, she will send Bob (via a classical channel) instructions about which of four operations to perform on his particle to create the state $|\psi\rangle$. These instructions can be encoded in two classical bits.

The mystery about exactly how the complex information contained in the state $|\psi\rangle$ got from Alice to Bob is an interesting problem in QIT. It could not have "piggy–backed" on the classical message Alice transmitted, since that was not nearly complex enough. Furthermore, Alice could potentially not have known exactly what state $|\psi\rangle$ was, so it would have been impossible for her to encode it. This and related issues will be discussed in Chapter 2.

The domain in which classical information theory and computation takes place has been supplanted in our understanding of fundamental physics by the quantum domain. In that sense, quantum information and computation represents a more fundamental understanding of the information sciences.

> In the meanwhile, the field of quantum information processing is constructing a unified theory of how information can be registered and transformed at the fundamental limits imposed by physical law. [9]

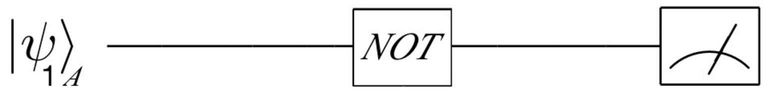
QIT represents a stunning breakthrough in our ability to achieve seemingly impossible tasks with respect to information encoding, encryption, and transmission. But perhaps the most promising domain for the exploitation of quantum effects in the information sciences is computation.

### 1.1.3 Quantum Computation

The field of quantum computation takes the concepts of QIT and studies the kinds of computational tasks that can be achieved. Quantum computers are composed (ideally) of noiseless quantum channels along which qubits can travel without undergoing any evolutions. The inputs to the computer can be controlled by the user, and the outputs are measurements with respect to a particular basis $\{|0\rangle, |1\rangle\}$, called the *measurement basis*.

Any transformations the qubits undergo, and any interactions between qubits traveling along their isolated channels, are perfectly controlled (ideally), and localized entirely within *gates*. There are several standard quantum gates (some of which are analogues of of the classical computer gates), out of which all quantum computational operations can be built.

Figure 1.1: A single qubit channel along which system A travels, with a controllable input state, a single quantum gate, and an output detector.




Some gates act on a single qubit, such as the $NOT$ gate in Figure 1. Figure 1 depicts a single qubit channel along which system $A$ travels, with a controllable input state $|\psi_1\rangle$. System $A$ encounters a $NOT$ gate, before ultimately reaching the output detector, which will effect a measurement with respect to the measurement basis $|0\rangle, |1\rangle$. The $NOT$ gate flips the state of the qubit from one definite state with respect to the measurement basis to the opposite state. That is, if the input $|\psi\rangle$ is $|0\rangle$, then after $NOT$, the output will be measured as $|1\rangle$, and vice versa.

It is often convenient to represent the state of systems and the operations performed by quantum gates in their matrix form:

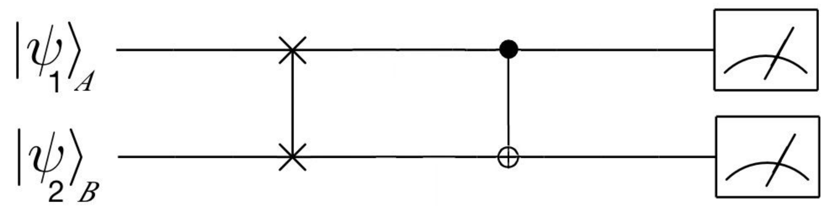
$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$
$$|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$
$$NOT = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

From this, it is clear to see that the action of $NOT$ on $|0\rangle$ will be $|1\rangle$:

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Some operators apply to multiple qubits simultaneously. Two such operators that will be relevant for the discussion of the D-CTC model are $SWAP$, which

Figure 1.2: A single qubit channel along which system A travels, with a controllable input state, a single quantum gate, and an output detector.




exchanges the states of the two systems on which it acts, and $CNOT$, which will perform a $NOT$ operation on the "target" qubit if and only if the "control" qubit is in the state $|1\rangle$. That is to say, $SWAP$ effects the following mapping:

$$|0\rangle_A |1\rangle_B \rightarrow |1\rangle_A |0\rangle_B$$
$$|1\rangle_A |0\rangle_B \rightarrow |0\rangle_A |1\rangle_B$$

And, when system $A$ is the control, and system $B$ the target, $CNOT$ effects:

$$|0\rangle_A |0\rangle_B \rightarrow |0\rangle_A |0\rangle_B$$
$$|0\rangle_A |1\rangle_B \rightarrow |0\rangle_A |1\rangle_B$$
$$|1\rangle_A |0\rangle_B \rightarrow |1\rangle_A |1\rangle_B$$
$$|1\rangle_A |1\rangle_B \rightarrow |1\rangle_A |0\rangle_B$$

The matrix form for $SWAP$ is:

$$SWAP = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The matrix form for $CNOT$ is

$$CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

These gates act on the joint state of two qubits. For example, the state $|1\rangle_A |1\rangle_B$ is represented as:

$$\begin{bmatrix} 0 \\ 1 \end{bmatrix}_A \otimes \begin{bmatrix} 0 \\ 1 \end{bmatrix}_B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}_{AB}$$

And the effect of $CNOT$ on this joint state is:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}_{AB} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}_{AB} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}_A \otimes \begin{bmatrix} 1 \\ 0 \end{bmatrix}_B = |1\rangle_A |0\rangle_B$$

The power of quantum computation comes in the fact that the states the systems are in when they are being operated on, or interacting, do not have to be definite eigenstates of the measurement basis. Recall, the equal superposition of measurement basis states yields two other useful states the qubits can be in:

$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}$$

$$|-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{bmatrix}$$

The effects quantum gates on systems in these superposed states are also well defined. For example, a $SWAP$ gate acting on two systems in the joint state $|0\rangle_A |+\rangle_B$ will yield $|+\rangle_A |0\rangle_B$:

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix}_A \otimes \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}_B = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \\ 0 \\ 0 \end{bmatrix}_{AB}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \\ 0 \\ 0 \end{bmatrix}_{AB} = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ 0 \\ \frac{1}{\sqrt{2}} \\ 0 \end{bmatrix}_{AB} = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}_A \otimes \begin{bmatrix} 1 \\ 0 \end{bmatrix}_B = |+\rangle_A |0\rangle_B$$

To represent a system that is entangled with other systems not directly under consideration, Deutsch adopts the *density matrix* formalism for representing states. This more general framework allows for a faithful representation of systems in definite states, and in superpositions, but gives us the resources to represent states that are entangled with external systems. Rather than single–column matrices, the state of a single qubit is represented as a $2 \times 2$ reduced density matrix. a density matrix $\rho$ for a general quantum state is equal to

$$\rho = \sum_i p_i |\psi_i\rangle \langle\psi_i|$$

In the case of a pure state$|\psi_P\rangle$, there is only one summand, and its probability is unity.

$$\rho_P = |\psi_P\rangle \langle\psi_P|$$

For example, for the state $|0\rangle$, the density matrix is:

$$\rho = |0\rangle \langle 0| = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$$

Entanglement among multiple systems, by definition, means that we cannot write down a definite state for any one system in isolation. If two particles are entangled, neither is in a definite state. Writing states as reduced density matrices, however, gives us the resources to write down a single matrix that encodes the probabilistic information about the outcome of a measurement made on one of the systems. This is called a mixed state. For example, consider the entangled state

$$\left|\Phi^+\right\rangle = \frac{1}{\sqrt{2}}\left(\left|0\right\rangle_A\left|0\right\rangle_B + \left|1\right\rangle_A\left|1\right\rangle_B\right)$$

The column matrix for this state is

$$\frac{1}{\sqrt{2}}\left(\begin{bmatrix}1\\0\\0\\0\end{bmatrix}_{AB} + \begin{bmatrix}0\\0\\0\\1\end{bmatrix}_{AB}\right) = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\\0\\1\end{bmatrix}_{AB}$$

This state is not equal to the tensor product of any two column vectors. Adopting the density matrix representation of this entangled state looks like this:

$$\rho = \frac{1}{2}\left(\begin{bmatrix}1&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}_{AB} + \begin{bmatrix}0&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&1\end{bmatrix}_{AB}\right) = \frac{1}{2}\begin{bmatrix}1&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&1\end{bmatrix}_{AB}$$

I can write down a reduced density matrix for the system $A$ that will encode the proper probabilities of outcomes of any measurements I can make on that system in isolation. If I trace out the degrees of freedom associated with subsystem $B$, I get:

$$\rho_A = \frac{1}{2}\begin{bmatrix}1&0\\0&1\end{bmatrix}$$

As we'll see below, Deutsch's solution to the paradoxes of time travel involves allowing the state of the system bound to the CTC to be in a mixed state. This allows him to identify a consistent fixed–point solution for any initial state traveling around the CTC.

The theoretical and experimental advances in quantum computation over the last several years have led many physicists and computer scientists to be very optimistic about the potential of future quantum computers. Although the development of the technology itself is in its infancy, there has been much work done on the particular types of algorithms which will be able to be implemented on these new computers. These quantum algorithms generally allow for exponential computational speed increases over their classical counterparts.

A commonly accepted interpretation of what is actually happening during a quantum computation is that the quantum states being exploited in the hardware allow for some sort of quantum parallelism taking place in either different branches of the wavefunction or, for the many-worlds theorists, in parallel universes (see e.g. [11] and [12]). According to these views, something about the nature of quantum measurement prevents us from accessing all of the computed information. There are particular algorithms, however, which allow us to extract enough information to be useful.

For example, in this passage from his [11], Deutsch famously issued a challenge to those who do not subscribe to the Many–Worlds Interpretation of quantum mechanics to explain how it is that Shor's algorithm—one of the canonical quantum computational algorithms—works:

> I mean provide an explanation. When Shor's algorithm has factorized a number using $10^{500}$ or so times the computational resources that can be seen to be present, where was the number factorized? [. . . ] Who did factorize it, then? How, and where, was the computation performed?

One can clearly see that Deutsch is assuming that each classical computational step has to take place *somewhere* in order for the quantum computation to be possible. It is clear that Deutsch's understanding even of basic notions of quantum information and computation is closely tied-up with the existence of parallel worlds. This feature of Deutsch's view will be explored in depth in Chapter 4.

## 1.2 Deutsch's CTC Model

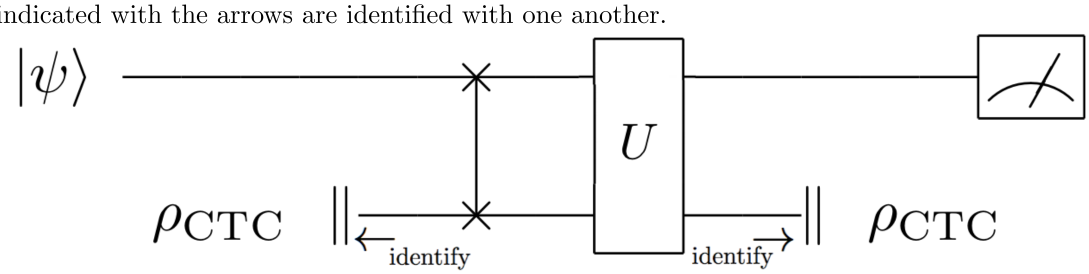
### 1.2.1 Introduction

The main focus of the papers collected in this dissertation is Deutsch's model for the behavior of quantum systems in the presence of Closed Timelike Curves (CTCs) first articulated in [1]. Deutsch aimed to integrate considerations about the possible states of physical systems allowed by quantum mechanics into an analysis of the paradoxes seemingly entailed by the possibility of time travel.

In addition to being a founding figure in QIT and quantum computation, Deutsch is also a well-known proponent of the Everett Interpretation of quantum mechanics. His D-CTC model is a perfect example of the combination of the two divergent approaches. The features of this model serve as a case study for the challenges of combining QIT with a richer underlying metaphysics.

The details of the model are described in Chapter 3. Here it suffices to say that Deutsch analyzes the information flow of a circuit that includes a "negative time delay". There are two spacelike surfaces that are identified, such that the qubit traveling along that channel, intersects with the forward surface, and continues out of the rear surface. The qubits on the information channels undergo no evolution whatsoever, except when they interact with other qubits in localized regions called "gates". Deutsch's goal is to analyze the potential physical situations of chronol-

Figure 1.3: A schematic representation of a CTC in Deutsch's standard form. There is a qubit bound to the CTC that interacts with the CR qubit only through quantum gates. The two surfaces indicated with the arrows are identified with one another.




ogy violation entirely in terms of their information–processing characteristics. All relevant physical features of the system are redescribed in this model in terms of information flow. This conception of a CTC preserves all of the information–flow features, without having to commit to any underlying spacetime geometry. Even so, for simplicity the two surfaces are often referred to as the "future mouth" and the "past mouth" of a wormhole.

Since the system entering the future mouth of the wormhole is identical to the system exiting the past mouth of the wormhole, it is natural to require that their states be the same. That is, there must be consistency between the state of the system on the CTC after it has undergone any interactions with the CR qubits, and the state of the system before it has undergone those interactions. The way Deutsch encodes this requirement is by imposing the following consistency condition:

$$\rho_{\text{CTC}} = \text{Tr}_{\text{sys}}[U(|\psi\rangle\langle\psi| \otimes \rho_{\text{CTC}})U^{\dagger}]$$

It says that the state of the system bound to the CTC when exiting the past mouth of the wormhole must be equal to the partial trace of the system after the action of the quantum gates (unitary operator $U$) on the system and any CR qubits (input state $|\psi\rangle$).

The details and implications of this consistency condition will be explored in Chapter 3, and its relationship to CCC will be explored in Chapter 4. Here I'll simply note that the D-CTC model has been critiqued for apparent inconsistencies (see [13] [14]and [15]), and it is not the only model for understanding the information flow of quantum systems traveling around CTCs. The rival P-CTC model, notably advocated by Seth Lloyd (see [16] and [17]), which is based on a different consistency condition, will be discussed in Chapter 4.

What follows is a brief description of the arguments contained in the papers collected in this dissertation.

## 1.3 Chapter Descriptions

### 1.3.1 Overview

The papers collected in this dissertation explore several issues surrounding David Deutsch's CTC model first introduced in his 1991 paper "Quantum Mechanics Near Closed Timelike Lines". Deutsch developed his model to account for the effects of quantum theory, which had been left out of classical discussions of time travel paradoxes. The fact that Deutsch formulated his model in terms of the information flow of quantum computational circuits supplemented by a negative time delay means that the model was well-suited for uptake in the quantum information science community.

The model has generated significant interest in QIT circles, particularly insofar as its computational predictions are concerned. However, I'll argue in Chapters 2 and 3 that a simple computational circuit supplemented by two qubits bound to a D-CTC leads to the prediction of Nonlocal Signaling, which is contrary to one of the fundamental principles of QIT. Furthermore, the attempt to rule out this prediction on QIT grounds falls afoul of one of the necessary presuppositions of Deutsch's model.

This presupposition—a substantial metaphysical assumption—is described in detail in Chapter 4. I argue in Chapters 4 and 5 that Deutsch's underlying metaphysical picture, which is necessary for the proper functioning of the D-CTC model, has internal tensions as well. Chapter 4 focuses on a problem with his purported solution to the Grandfather Paradox, and Chapter 5 focuses on a problem with his purported solution to the Knowledge Paradox.

Deutsch's model is an attempt to bring together elements of the QIT approach with a substantial metaphysical picture. The tensions inherent in it provide an angle from which we can examine the general possibility of marrying the QIT approach with the more traditional metaphysical approaches to shoring up the foundations of quantum theory. In Chapter 3 I examine the features of the QIT approach and Deutsch's particular metaphysical picture that are in conflict. In Chapter 6 I draw a comparison between an attempted full interpretation of quantum theory based on the principles of QI, due to Bub and Pitowsky, with a particular recently–proposed framework that aims to offer an analysis of the metaphysical approaches, due to Allori and others.

### 1.3.2 Chapter 2: Nonlocal Signaling and Superluminal Information Transmission in Quantum Theory

The prohibition of the possibility of *signaling* in quantum mechanics has played an important role in the development of the conceptual foundations of the theory since the famous "No Bell Telephone" result. It has been adopted as one of the core characteristic principles of quantum theory, and in quantum information more generally. The No-Signaling Principle is also sometimes seen as a point of contact between quantum theory and relativity theory. After all, the prohibition against exploiting quantum effects to send information faster than the speed of light seems to lend credence to Einstein's principle that nothing can be accelerated to speeds faster than $c$. However, in this paper I will argue that the notion of signaling prohibited by quantum theory is conceptually distinct from the relativistic principle. As such, relativity cannot be adopted as a justification for the inclusion of the No-Signaling Principle in quantum mechanics. I introduce a distinction between what I term *Superluminal Information Transfer*, in which a carrier of information must physically traverse the space in between the communicating parties faster than light, and *Nonlocal Signaling*, which does not have this feature. Relativity clearly rules out the former kind, but it is argued that signaling by exploiting quantum entanglement is of the latter kind.

### 1.3.3 Chapter 3: Would the Existence of CTCs Allow for Nonlocal Signaling?

A recent paper from Brun et al. has argued that access to a closed timelike curve (CTC) would allow for the possibility of perfectly distinguishing nonorthogonal quantum states [18]. I show how this result can be used to develop a protocol for instantaneous nonlocal signaling, and detail the debate surrounding these results. Several commenters have argued that nonlocal signaling must fail in this and in similar cases, for various reasons. I argue that each of these objections fails to rule out Nonlocal Signaling in the presence of a CTC. I argue that the reason these authors are motivated to exclude the prediction of nonlocal signaling is because the No Signaling principle is considered to a fundamental part of the formulation of the quantum information approach. I draw out the relationship between nonlocal signaling, quantum information, and relativity, and argue that the principle theory formulation of quantum mechanics, which is at the foundation of the quantum information approach, is inconsistent with Deutschs D-CTC model, on which this protocol is based.

### 1.3.4 Chapter 4: The Metaphysics of D-CTCs: On the Underlying Assumptions of Deutsch's Quantum Solution to the Paradoxes of Time Travel

I argue that Deutsch's celebrated model for the behavior of systems traveling around closed timelike curves (CTCs) relies implicitly on a substantive metaphysical assumption. The D-CTC model is widely adopted by those working on research in quantum foundations and CTCs, many of whom would likely be uncomfortable with this metaphysical commitment. Deutschs model is considered to have shown that quantum theory has the resources to solve the paradoxes of time travel without recourse to a strict superdeterministic global consistency condition (as in the classical case). I argue that Deutsch is actually employing a version of quantum theory with a significantly supplemented ontology of parallel existent worlds. These worlds differ in kind from the many worlds of the Everett interpretation. Standard Everett does not support the existence of multiple identical copies of the world, which the D-CTC model requires. Worlds branch only when there is a significant enough difference to cause macroscopically distinguishable states via decoherence.

However, Deutsch's solution to the paradoxes of time travel require that there be such a structure of parallel worlds in existence. This feature of Deutsch's view has been obscured, since he often refers to the branching structure of Everett as a "multiverse", and for convenience describes the phenomenon of quantum interference by reference to parallel interacting definite worlds. But he admits that this is only an approximation to the Everett interpretation. In the context of his work on CTCs, however, he relies crucially on the existence of a multiverse of parallel interacting worlds. These worlds cannot be the result of the standard Everett interpretation. Therefore, I argue, Deutsch's model does not represent a quantum solution to the paradoxes of time travel. The model is supplemented by structures that go significantly beyond quantum theory, and play an ineliminable role in its predictions and explanations.

### 1.3.5 Chapter 5: Shakespeare's Free Lunch: A Critique of the D-CTC Solution to the Knowledge Paradox

In this paper I argue that the consistency condition from the D-CTC model differs significantly from the classical consistency condition found in Lewis [19] and Novikov [20], as well as from the consistency condition found in the P-CTC model, the major rival to Deutsch's approach. Both the CCC and the P-CTC consistency condition are formulable in the context of a single history of the world. Deutsch's consistency condition (as argued in Chapter 4) relies on the existence of parallel worlds. I argue that Deutsch's commitment to realism about parallel worlds puts his solutions to the information paradox in jeopardy. The information paradox is the most strongly motivating problem for Deutsch, and he considers his model to succeed in solving it. I argue that, because of Deutsch's commitment to this metaphysical picture, he is committed to the existence of physical situations that are in every way indistinguishable from the paradoxes he attempts to rule out by adopting the model in the first place. This chapter critiques Deutsch's proposed solution to the Knowledge Paradox, arguing that his commitment to the actuality of the many worlds of the Everett interpretation (on which he relies to solve the paradoxes) guarantees the existence of worlds that are indistinguishable from worlds in which the genuine Knowledge Paradox arises.

### 1.3.6 Chapter 6: On the Commons Structure of the Primitive Ontology Approach and the Information–Theoretic Interpretation of Quantum Theory

The kind of comparative considerations that come up at the end of Chapter 3 are expanded in Chapter 6. The differences between foundational approaches to quantum theory based on the quantum information–theoretic assumptions and those based on certain metaphysical commitments is exemplified by comparing the Quantum Information–Theoretic Interpretation of quantum theory to the Primitive Ontology approach, due to Allori, Goldstein, and others.

The key feature of an information–theoretic interpretation of quantum theory is that it conceives of the fundamental formulation of a physical theory to be in terms of inviolable principles, rather than in terms of an ontology and a dynamics. I argue in Chapter 3 that this has implications on the fit of the D-CTC model into QITI. Chapter 6 is an example of the direction a research program that aims to understand the relationship between foundational approaches based on the QIT framework, and foundational approaches based on metaphysical considerations could take.

Deutsch's CTC model is a combination of the two approaches. While Deutsch himself isn't explicit about this fact, it is because he is drawing on the resources of quantum theory that his model can solve the paradoxes in the ways it does. However, I argue in Chapters 4 and 5 that this blurring of the lines between the QIT framework in which he formulates his model, and the metaphysical presuppositions he makes to ensure the model behaves the way he wants it to creates serious problems for him.

I use the primitive ontology framework of Allori et al. to analyze the quantum information-theoretic interpretation of Bub and Pitowsky. There are interesting parallels between the two approaches, which differentiate them both from the more standard realist interpretations of quantum theory. Where they differ, however, is in terms of their commitments to an underlying ontology on which the manifest image of the world supervenes. Employing the primitive ontology framework in this way makes perspicuous the differences between the quantum information-theoretic interpretation, and the various realist interpretations of quantum theory. It also allows us to identify a sense in which the commitments of quantum information-theoretic interpretation are underspecified. Several possible ways of completing the interpretation are presented, and it is suggested that the most likely strategy would leave the information-theoretic interpretation such that it would fail to qualify as a theory, according to the primitive ontology approach.

### 1.3.7 Conclusion

In conclusion, I make some observations about the relationship between the quantum information-theoretic approach to the interpretation of quantum theory, and the approaches focused primarily on arguing for one or another underlying ontology. Deutsch's model is situated squarely in the latter camp. It serves as a useful example in pulling apart the implications of the two approaches. I argue that the quantum information-theoretic interpretation of quantum theory, in denying the fundamentality of any particular ontology, in favor of kinematical principles, is inconsistent with the metaphysical commitments of the Deutsch model. Deutsch's interpretational stance is among the metaphysically-motivated positions. I argue that this element of the Deutsch model is essential to the solutions it offers to the paradoxes of time travel, and therefore the D-CTC model cannot be adopted without implicitly endorsing Deutsch's metaphysical commitments. This feature makes the D-CTC model an uncomfortable fit with the quantum information approach.

# Chapter 2: Nonlocal Signaling and Superluminal Information Transfer in Quantum Theory

## 2.1 Introduction

In this paper I will develop and articulate the conceptual distinction between Nonlocal Signaling (NS) and Superluminal Information Transfer (FTLIT). This distinction is useful because the relativistic prohibition against material particles attaining speeds greater than $c$ is sometimes taken as a justification for ruling out the possibility of signaling in the context of quantum mechanics. This distinction allows us to see why this view is mistaken.

There are certain interesting similarities between the relativistic prohibition against faster-than-light travel and the No Signaling theorem of quantum mechanics. But the fact is that the relativistic concept and the quantum mechanical concept are distinct. CTCs (and other nonlinear extensions) provide a good example of a context in which this distinction makes a difference. So if you want to have a No-Signaling Principle as part of a more general framework in which you can embed quantum theory, you have to find another way of justifying it, and you can't point to relativity as a justification. Likewise, when analyzing No-Signaling in quantum mechanics, you have to divorce it from mere FTL information transmission.

This difference allows us to formulate the notions of Nonlocal Signaling and Superluminal Information Transfer, which are useful to distinguish in the context of QIT. FTLIT is the more familiar concept, which involves a carrier of information actually traversing the spacetime separating the communicating parties faster than $c$. Nonlocal Signaling, however, is based entirely on using quantum entanglement to generate information in a distant location without there being anything actually traveling between the communicating parties.

The relativistic constraint applies to FTLIT, but not to NS. Therefore the notion of signaling that seems to be threatened by nonlocal quantum correlations is distinct from the idea of faster-than-light communication that is ruled out by SR.

I will begin by describing the quantum teleportation protocol in order to motivate the idea of signaling in quantum mechanics. In Section 3 I will discuss an argument from Nicolas Gisin's [21] to the effect that any model that attempts to explain the correlations of entangled quantum systems by appeal to any combination of direct–causal and common–causal factors (models which he calls "$v$–causal") will give rise to the possibility of FTLIT. Gisin's work is relevant to the dissertation because he begins by arguing that, if a certain condition holds, superluminal direct causes are not inconsistent with relativity. He argues that if there were superluminal (but finite) direct causal factors responsible for the existence of the observed quantum correlations, we would be able to exploit them to sent FTLIT messages. If we were able to rule out $v$–causal models, then we would need to give up on the idea that there are continuous local causal factors responsible for the quantum correlations. Despite having most of the elements of the NS–FTLIT distinction on the table, Gisin still equates quantum signaling with FTLIT. This elision of the distinction doesn't have a negative impact on the point Gisin is arguing, however.

I will then move on to discuss Christopher Timpson's analysis of the teleportation protocol from his book *Quantum Information Theory and the Foundations of Quantum Mechanics* [22]. He argues that, in the context of quantum theory, information transmission cannot be thought of as a continuous process. Rather, a new token of the same information type is created at the second location without the information needing to traverse the intervening space from its source.

In the final section, I synthesize elements of Gisin's and Timpson's positions to develop the distinction between NS and FTLIT. I argue with Gisin that the transmission of information between two spacelike–separated parties is not inconsistent with relativity. And I argue with Timpson that, in the context of QIT, this should not be thought of a continuous process.

## 2.2 Teleportation and Signaling

Nonlocal Signaling will play an important role in the argument presented in this dissertation. In this section, I will explain the concept of *signaling* in quantum theory, and why it is impossible in standard quantum contexts. In Chapter 3, the discussion will center around the possibility of signaling in an extension of quantum theory that is induced by the presence of a D-CTC. But for the purposes of this chapter, I will introduce a black–box "signaling device", the operation of which will go unanalyzed.

In order to fully understand the concept of signaling, it is best to understand its closest allowed quantum counterpart, teleportation. I will begin this section by detailing the teleportation protocol, and then proceed to introduce signaling.

### 2.2.1 Teleportation

The quantum teleportation protocol is one of the most striking implications of quantum theory. Here it is presented in detail, diagrammed as a quantum circuit.[1]

Alice begins with an input system $I$ in a potentially unknown state, that she wishes to transmit to Bob. The qubit can be in any state $|\psi\rangle_I$, and unless she prepared it herself, she will have no way of knowing what that state is. There is no measurement that she can perform that will give her certain knowledge of the state $|\psi\rangle_I$. If she chooses to measure the qubit in a basis different from the one in which the state $|\psi\rangle_I$ was prepared, she will get a definite outcome with respect to her chosen basis, but the final state of the system will not give her any certain knowledge about the state $|\psi\rangle_I$ itself. If she happens to choose a measurement of the basis in which the state was prepared, the output will correctly register $|\psi\rangle_I$, but she will have no way of knowing for certain that she has chosen correctly.

Even if she was aware of $|\psi\rangle_I$, the information necessary to specify the exact state is potentially infinite. This is because the state $|\psi\rangle_I$ is an arbitrary linear

[1]This section follows the presentation from [23].

combination of the eigenstates of the measurement basis:

$$|\psi\rangle_I = \alpha|0\rangle_I + \beta|1\rangle_I$$

The coefficients $\alpha$ and $\beta$ can take on any complex value, subject to the condition that $|\alpha|^2 + |\beta|^2 = 1$. Therefore, to perfectly specify the value of either one of the coefficients, one would in general be required to send a message encoding a complex-valued number.[2]

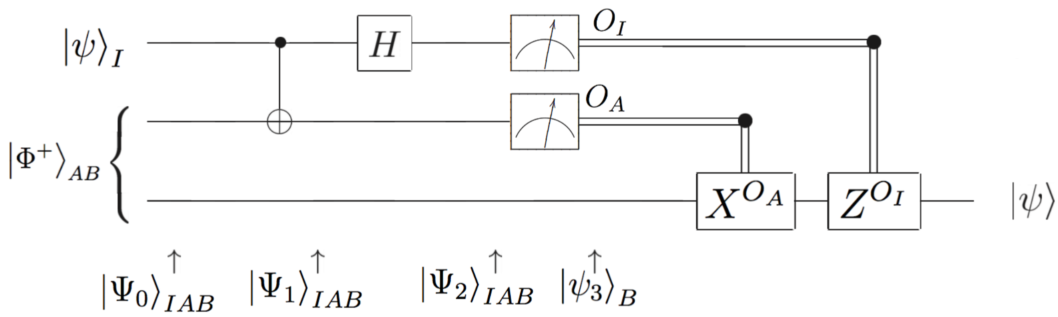
However, the situation changes drastically when Alice and Bob share a maximally entangled state.

$$|\Phi^+\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B\right)$$

This state is a state of perfect correlation, meaning that if Alice and Bob perform the same measurement, they will always get exactly the same outcome. With this shared resource, Alice and Bob can implement a protocol that allows Alice to perfectly transmit the state $|\psi\rangle_I$ to Bob, using only two classical bits.

[2]There are a number of interesting results related to this point, answering the question of how much classical information would need to be transmitted from Alice to Bob for them to simulate the outcomes of measurements on a pair of entangled qubits. That is, how much classical information needs to be passed between them to give rise to the same correlations that obtain when they share a maximally entangled quantum state? Maudlin was one of the first to work on the problem, and he found that, on average, the quantum correlations can be matched using 1.174 bits, but in the worst case the communication would have to be infinite [24]. Another protocol proposed by Brassard, Cleve and Tapp limited the maximum amount of information needed to 8 bits, provided that Alice and Bob could have an infinite amount of shared randomness [25]. In other proposed protocols, the average information transfer needed to simulate the quantum correlations was similar to that of Maudlin's findings (1.48 bits [26] and 1.19 bits [27]). In 2003 Toner and Bacon articulated a remarkable protocol in which only 1 bit per round is needed to perfectly simulate quantum correlations [28].

Figure 2.1: A quantum circuit implementing the teleportation protocol. The double lines exiting Alice's measurement gates represent the transmission of classical bits. Adapted from [23].




The joint initial state $|\Psi_0\rangle_{IAB}$ of the entire system is

$$|\psi\rangle_I |\Phi^+\rangle_{AB} = \frac{1}{\sqrt{2}} [\alpha |0\rangle_I (|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B) + \beta |1\rangle_I (|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B)]$$

Alice begins by performing the joint measurement CNOT on the the two qubits over which she has control—systems $I$ and $A$. This yields the overall state

$$|\Psi_1\rangle_{IAB} = \frac{1}{\sqrt{2}} [\alpha |0\rangle_I (|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B) + \beta |1\rangle_I (|1\rangle_A |0\rangle_B + |0\rangle_A |1\rangle_B)]$$

Alice then sends system $I$ through a Hadamard gate, which performs the following mapping:

$$|0\rangle \rightarrow \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)$$

$$|1\rangle \rightarrow \frac{1}{\sqrt{2}} (|0\rangle - |1\rangle)$$

This yields the joint state

$$|\Psi_2\rangle_{IAB} = \frac{1}{2} [\alpha (|0\rangle_I + |1\rangle_I) (|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B) + \beta (|0\rangle_I - |1\rangle_I) (|1\rangle_A |0\rangle_B + |0\rangle_A |1\rangle_B)]$$

This state can be rewritten as

$$|\Psi_2\rangle_{IAB} = \frac{1}{2}\left[|0\rangle_I |0\rangle_A (\alpha |0\rangle_B + \beta |1\rangle_B) + |0\rangle_I |1\rangle_A (\alpha |1\rangle_B + \beta |0\rangle_B) \right.$$
$$\left. + |1\rangle_I |0\rangle_A (\alpha |0\rangle_B - \beta |1\rangle_B) + |1\rangle_I |1\rangle_A (\alpha |1\rangle_B - \beta |0\rangle_B)\right]$$

Alice will then measure the states of her two qubits in the measurement basis, yielding one of four possible states:

$$O_1 : |0\rangle_I |0\rangle_A$$
$$O_2 : |0\rangle_I |1\rangle_A$$
$$O_3 : |1\rangle_I |0\rangle_A$$
$$O_4 : |1\rangle_I |1\rangle_A$$

The outcome of these measurements will give her a value of 0 or 1 for system $I$, and likewise for system $A$.

$$O_I : 0 \text{ or } 1$$
$$O_A : 0 \text{ or } 1$$

Notice that each of the four states is associated with a unique state of Bob's system $B$. By making a measurement on her systems, Alice learns about the state of Bob's system (labeled $|\psi_3\rangle_B$ in Figure 2.1).

$$|0\rangle_I |0\rangle_A \Longrightarrow |\psi_3\rangle_B = \alpha |0\rangle_B + \beta |1\rangle_B$$
$$|0\rangle_I |1\rangle_A \Longrightarrow |\psi_3\rangle_B = \alpha |1\rangle_B + \beta |0\rangle_B$$
$$|1\rangle_I |0\rangle_A \Longrightarrow |\psi_3\rangle_B = \alpha |0\rangle_B - \beta |1\rangle_B$$
$$|1\rangle_I |1\rangle_A \Longrightarrow |\psi_3\rangle_B = \alpha |1\rangle_B + \beta |0\rangle_B$$

Each of these four states of Bob's system $B$ are closely related to the initial input state $|\psi\rangle$. In fact, the first of them is identical to it. If Alice measures the outcome $|0\rangle_I |0\rangle_A$, she knows that Bob has the state $|\psi\rangle$ in hand. Now all that remains is to communicate this information to him.

Since both Alice and Bob know the protocol, the simplest message Alice can send to Bob is the result of her outcome $(O_I O_A)$, which is two classical bits. If she sends Bob the message "00", Bob knows that he has $|\psi\rangle$ in his possession.

However, if Alice gets any of the other outcomes, she needs to communicate instructions to Bob about how to transform the state of his system into the target state $|\psi\rangle$. The operations required of Bob are very simple. In the case that Alice measures the outcome $|0\rangle_I |1\rangle_A$, she learns that Bob's system is in the state $X|\psi\rangle$ (as if $|\psi\rangle$ had encountered a $NOT$ gate). If Bob were to reverse the effect of the $NOT$ gate on his system, he would end up with the state $|\psi\rangle$. A second application of $NOT$ does the trick.

Similarly, if Alice measures the output $|1\rangle_I |0\rangle_A$, she knows Bob has the state $Z|\psi\rangle$, and if she measures $|1\rangle_I |1\rangle_A$, she knows Bob has the state $X \circ Z|\psi\rangle$. She is able to communicate via a simple (classical) two–bit string all the information Bob needs to produce the input state $|\psi\rangle$. The sequence of transformations Bob needs to apply to his qubit $|\psi_3\rangle_B$ to yield the input state is

$$X^{O_A} \circ Z^{O_I}$$

This is a powerful and classically unprecedented protocol that provides one of the clearest insights into the unique abilities quantum mechanics provides for manipulating information. Teleportation will be important for the point being argued in this paper, as well as for the discussion of the P-CTC model that will come up in Chapter 5. But perhaps the most important feature of the teleportation protocol is that it raises the issue of the seemingly supernatural ability to send information instantaneously across arbitrarily large distances. Quantum entanglement seems to allow Alice to bring into existence, in Bob's location, a particular quantum state. Consider the case where Alice gets the outcome $|0\rangle_I |0\rangle_A$. The instant she measures the state of her two systems, the entanglement she shared with Bob's system is broken, and his system is forced into the state $|\psi\rangle$. The only feature of this scenario that prevents this instantaneous effect is that Bob cannot *know* that his system is now in the state $|\psi\rangle$. This epistemic limitation is the only thing standing in the way of the ability to communicate instantaneously between distant parties. This concept is called *signaling*, and it is not allowed by quantum mechanics. But exactly *why* it is not allowed is a matter of some controversy, and will be a main focus of this and the following chapter.

### 2.2.2 Signaling

While the teleportation protocol doesn't allow Alice to send usable information to Bob at superluminal speeds, it does suggest that the quantum information itself reaches Bob instantaneously, but it is unavailable until the two classical bits of information are received. This allows us to formulate the following question: Is there any protocol by which Alice could exploit quantum entanglement to send Bob usable information instantaneously? This concept is known as *signaling*. Ordinarily quantum theory says that this is impossible.[3] In order to more fully understand why this is the case, here I will present a brief introduction to the concept.

Consider a case where Alice and Bob share a pair of entangled quantum particles. Alice's particle $A$ is under her control in her laboratory, and Bob's particle $B$ is under his control in his laboratory at a spatially separated location. Alice and Bob can each choose one of two measurements to make on their qubits, and they will get one of two outcomes. Alice's choice of measurement is represented as $x$, and Bob's choice of measurement is represented as $y$. The outcome of Alice's measurement is $a$, and the outcome of Bob's measurement is $b$. For example, Alice might have the choice to perform a measurement in the basis $\{|0\rangle, |1\rangle\}$ or in the basis $\{|+\rangle, |-\rangle\}$. For either choice of measurement she makes, she will either get the outcome "0" (representing $|0\rangle$ in the $\{|0\rangle, |1\rangle\}$ basis or $|+\rangle$ in the $\{|+\rangle, |-\rangle\}$ basis), or "1" ($|1\rangle$ or $|-\rangle$, depending on the choice of measurement). When Alice and Bob share a maximally entangled pair of particles, the following correlations obtain:

$$p(a = b|x = y) = 1$$

When they make the same measurement, they will get the same outcome. But locally neither Alice nor Bob can deduce anything about the measurement setting

[3] In Chapter 3 we will consider extraordinary circumstances (namely, access to a D-CTC) in which quantum mechanics seems to predict signaling. There has been some debate about what to conclude in these cases, and that will be the focus of the latter half of that chapter.

chosen by the other.

$$p(a|x = y) = p(a|x \neq y)$$

and

$$p(b|x = y) = p(b|x \neq y)$$

The probabilities of the outcomes Alice and Bob measure are uninformative about the measurement settings of the other party.

Signaling obtains in cases where these equivalences fail. If the outcome seen by Bob gives him any information whatsoever about the input chosen by Alice, a protocol can be developed that will allow them to exploit this relationship to send information. Signaling can be probabilistic, in which case many runs of the experiments must be carried out in order for Bob to be certain of which bit value Alice is sending, or it can be deterministic, such that Bob will be certain which bit value Alice is sending him after a single measurement.

Standard quantum mechanics rules out the possibility of signaling. If you look at the probabilities for Alice in isolation, for example, when considering the maximally entangled state

$$\left|\Phi^+\right\rangle_{AB} = \frac{1}{\sqrt{2}} \left(|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B\right)$$

If she chooses to measure her particle with respect to the basis $\{|0\rangle, |1\rangle\}$, she will see each possible with equal probability.

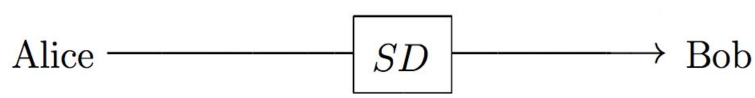
This has led to widespread acceptance of the *No Signaling Principle* as one of the fundamental features of the quantum world.

> The no-signalling principle states that $A$'s marginal is independent of of $B$'s choice, $p(a|x,y) \equiv \sum_b p(a,b|x,y) = p(a|x)$, and $B$'s marginal is independent of $A$'s choice, $p(b|x,y) = p(b|y)$ [21]

A discussion of the No Signaling Principle is central to the argument in Chapter 3.

However, the concept of signaling allows us to consider it to be a potential channel along which classical information can be sent. If Alice and Bob were in possession of a hypothetical signaling device (SD), it would allow Alice to send a classical message to Bob.

Figure 2.2: A hypothetical signaling device creates a channel for quantum information from Alice to Bob. The input Alice chooses causally influences the output Bob will see at speeds faster than the speed of light, possibly instantaneously.




What is it exactly that prevents such a device from existing? There are epistemic considerations that seem to be playing a central role, as discussed in the teleportation section above. But would signaling run afoul of relativity theory, as is so often claimed? (See e.g. [29], [30], [22].)

Bub and Pitowsky, in "Two Dogmas About Quantum Mechanics", argue that the No Signaling Principle is best understood as concerning the separability of quantum states, as opposed to relativity.

Note that 'no signaling' is not specifically a relativistic constraint on

> superluminal signaling. It is simply a condition imposed on the marginal probabilities of events for separated systems, requiring that the marginal probability of a B-event is independent of the particular set of mutually exclusive and collectively exhaustive events selected at A, and conversely, and this might well be considered partly constitutive of what one means by separated systems. [31]

Ever since Einstein raised the issue of separability in the debate following the publication of the EPR paper, it has been a focus of the discussion surrounding entanglement [32] [33]. What Bub and Pitowsky are suggesting here is that the No Signaling Principle can be seen as ensuring that physical systems that are distant from one another in space are genuinely distinct, despite the fact that nonlocal correlations obtain between them.

Consider the following example: Imagine Alice uses her signaling device to send a message to Bob. However, Bob doesn't make the measurement on his system until enough time has elapsed that a lightlike signal *could* have traversed the space between them. Alice sent no such signal, yet Bob still receives the message. This illustrates that the puzzling feature of signaling is not that it is at odds with the relativistic constraint against the transmission of information faster than the speed of light. Rather, it is the fact that Alice seems to have direct control over the state of Bob's system even though no direct causal influence travelled through space from Alice's location to Bob's. This feature is present in the teleportation protocol as well, though no useable information can be extracted. However, this is the only relevant difference between signaling and teleportation. It is a thin epistemic line that divides them.

## 2.3 Gisin's $v$–causal Models

Nicolas Gisin makes the interesting observation that any explanation of quantum correlations that relies on direct causation being propagated at some finite superluminal speed $v$, will give rise to the ability to send signals at $v$ [21]. He calls a model based on superluminal direct causes (with the possible inclusion of common causes) "$v$–causal".

Consider the teleportation protocol described above. It seems as though Alice's measurement forces Bob's system into one of the the four possible states in which it could potentially end up. A $v$–causal model of this process explains the observed correlations in the outcomes of their measurements in terms of a undetectable direct causal influence traveling from Alice to Bob at superluminal speeds.

The immediate objection this argument raises has to do with consistency with relativity. Isn't the propagation of information at superluminal speeds in conflict with the prohibition against anything traveling faster than $c$? Gisin argues that unrestricted superluminal signaling would indeed be inconsistent with relativity, but the model he has in mind includes a privileged reference frame in which the speed of the $v$–causal influence is defined. This assumption, Gisin claims, is not contrary to the spirit of relativity.

Tim Maudlin also argues that superluminal causal influence is not inconsistent with relativity in his book *Quantum Non-locality and Relativity.*

> And we have further found that none of the restrictions can be derived, in any strictly formal sense, from the Lorentz transformations, or from the fundamental relativistic space-time structure. On the contrary, explicitly relativistic theories of tachyons and of superluminal signals have been constructed. The fundamental feature of the Lorentz transformations is that they leave the speed of light invariant, not that they render it an insuperable boundary. [34]

Maudlin disagrees with Gisin, however, claiming that a privileged reference frame would violate a "fundamental relativity principle". Yet he develops models that he argues are consistent with relativity, in which superluminal casual influences obtain.

Both authors agree that the ability to send usable information faster than light is not alone sufficient for a conflict with relativity, even considering the danger that this raises for sending information to the past. As Maudlin says

> The claim that relativity forbids signals which travel faster than light is often made without justification and accepted without demur. [34]

For Gisin's $v$–causal model, a privileged reference frame is assumed, in which causal ordering is defined, forestalling the objection that the ability to use superluminal signals to send information to the past could undermine a definite causal order of events. In this frame alone, the influence from Alice to Bob is traveling at its maximal speed of $v$. There will be frames in which Bob appears to receive the $v$–causal influence prior to Alice making her measurement, but this will be nonfundamental.

The next objection that the $v$–causal model must immediately address in order to proceed involves the empirical results that seem to establish the existence of nonlocal correlations. The Aspect experiments are the best–known results of this type [35] [36]. However, due to practical problems of synchronization of the distant measuring devices in the two wings of the experiment, all that has in fact been established is a lower bound on the speed $v$ of the hidden causal influence. Further experiments have been carried out by Gisin's research group that have set this lower bound for various possible candidates of the privileged reference frame, including the frame at rest with respect to the surface of the Earth, the frame at rest with respect to the CMB, and scanning all possible privileged frames. These experiments have set the lower bound for $v$ at approximately 50,000 times the speed of light [37] [38] [39] [40].

The protocol for sending messages at the superluminal speed $v$ in the privileged reference frame involves three parties. Alice, Bob, and Charlie share three maximally-entangled particles in a GHZ state

$$\Psi = \frac{1}{\sqrt{2}} \left( |000\rangle + |111\rangle \right)$$

Bob and Charlie are right next to one another in the laboratory, such that they can synchronize the measurements they make on their particles. Since their measurements are perfectly correlated, the $v$–causal influence cannot travel from $B$ to $C$ in time to cause their results to be correlated. Therefore, Bob and Charlie's results will be uncorrelated. Alice is in a distant location. At an appointed time, Bob and Charlie make synchronized measurements on their two particles. If Alice wants to send the message "yes", she makes a measurement on her particle before the appointed time, such that a light signal could not reach Bob and Charlie from her location, but the $v$–causal influence could. In this case, all three will obtain the same outcome, which Bob and Charlie can compare immediately. If Alice wants to send the message "no", she does not make a measurement on her particle. Since Bob's and Charlie's measurements are perfectly synchronized, there is no time for the $v$–causal influence to ensure that they get the same outcome. Therefore, they will have uncorrelated results. If over several runs they measure different outcomes approximately half the time, they can infer that Alice has not made the measurement in her laboratory, and has therefore intended to send the message "no".

In order to test the $v$–causal model, Gisin proposes an Aspect-like experiment meant to show that

> 1. either the hypothetical hidden influence can't remain hidden, but necessarily leads to signalling and faster-than-light communication,
> 2. or, all $v$–causal explanations are ruled out, i.e. no combination of Direct Cause and local Common Cause can explain the experimental result. [21]

Gisin considers his $v$–causal models for the quantum correlations to be motivated by considerations of consistency with the Newtonian Principle of Continuity, according to which all influences must travel continuously from cause to effect. If the Principle of Continuity were true, and the quantum correlations were the result of a causal influence propagated at some $v > c$, then we could use this influence to send information at $v$. If we were to discover, through his proposed Aspect–like results in the right reference frame that we cannot send messages faster than $c$, then there cannot be an influence that propagates at $v$.

The failure of the Principle of Continuity as an explanation for the existence of quantum correlations leads him to consider the possibility of the ability to signal without a $v$–causal model. He calls this model of signaling "non–physical".

> Hence, assuming only local Common Causes carried by the (localized) physical systems in Alice and Bob's hands, signalling would be non-physical communication. [21]

In his 2013 book *Quantum Information Theory and the Foundations of Quantum Mechanics*, Christopher Timpson suggests a way in which we might make physical sense of superluminal discontinuous causal influence.

## 2.4 Timpson's Analysis of Teleportation

Christopher Timpson's analysis of the information-theoretic features of non-local quantum effects makes the case that there is no carrier of information being transmitted between the two distant locations. Timpson's analysis takes place in the context of a discussion of quantum teleportation, but I will argue in Section 2.5 that his position applies equally well to the case of signaling.

Timpson argues by way of conceptual (and linguistic) analysis that "information" in the technical sense—as it appears in Information Theory, which he denotes as "information$_t$" so as to distinguish it from the non-technical notion—is an abstract noun, which does not refer to "a spatio-temporal particular, to a concrete entity, or to a physical substance" [22]. He argues that we shouldn't think of information as being an entity that is somehow transported from one location to another.

Rather, "information transmission" needs to be understood as a physical process in which a new token of information$_t$ is created at $B$ that is necessarily preceded by the existence of another token of that same type having existed at $A$. There is no *thing* traversing the space between $A$ and $B$. Rather, there is a physical process that results in another token of the information$_t$ being created. Since no physical entity of any kind need pass between $A$ and $B$ for this to be the case, there is nothing that need travel faster than the speed of light.

He believes that we are led astray when we take the phrase "the information$_t$" to denote a particular.

> The assumption [...] is that we need to provide a story of how some located *thing* denoted by 'the information$_t$' travels from Alice to Bob. Moreover, it is assumed that this supposed thing should be shown to take a spatio-temporally continuous path. [22]

By recognizing "information$_t$" as an abstract noun, we solve this problem. Furthermore, this recognition provides us with the only legitimate reading of the question of how the information$_t$ "got to Bob". It is a question that is answered by reference to the physical processes that produce at $B$ another token of the information$_t$ that was tokened at $A$. In the case of quantum information protocols, this answer will be quantum mechanical.

In the teleportation protocol, information$_t$ (which, in this case, is the unknown quantum state $|\psi\rangle$) is tokened at location $A$, and subsequently tokened at location $B$, having been caused by a nonlocal physical process. The process itself is quantum mechanical, and doesn't admit of any deeper physical explanation. The Principle of Continuity does not apply to the quantum correlations.

In what sense, then, is this *transmission* of information? If nothing traverses the intermediary space between Alice and Bob, can we truly say that anything is being transmitted? Timpson says

> I am not claiming that there is no such thing as the transmission of information$_t$, but simply that one should not understand the transmission of information$_t$ on the model of transporting potatoes, or butter, say, or piping water. [...] The transmission of a piece of information$_t$ from $A$ to $B$ will consist in the production at $B$ of another token of the type produced at $A$, where the production at $B$ is consequent on the token's being produced at $A$. [22]

He argues that the unique feature of the teleportation protocol is that the information$_t$ can be tokened at $B$ subsequent to its having been tokened at $A$, but cannot be tokened at any point in between $A$ and $B$ in the meantime. This is equivalent to a failure of the Principle of Continuity discussed by Gisin. While this possibility struck Gisin as "non–physical", Timpson's analysis suggests that it is *because* of the truth of quantum physics that such a thing is possible.

However, unlike Gisin, Timpson is not interested in considering superluminal signaling. He relies on the argument that the impossibility of signaling is due to the constraint from relativity.

> How is this to be reconciled with some of the ways we often talk about information in physics, especially the example of relativity, where the most natural way of stating an important constraint is to say that relativity rules out the propagation of *information* faster than the speed of light? [22]

Timpson's answer is that signaling is ruled out for the reason that it makes causal ordering ambiguous in some reference frames. In particular, this ambiguity leads to the possibility of a closed timelike loop of information, which could be used to enact a Grandfather Paradox.

> The constraint is that superluminal signalling is ruled out on pain of temporal loop paradoxes. What this means is that no *physical process* is permissible that would allow a signal to be sent superluminally and thus allow information to be transmitted superluminally. What are ruled out are certain types of physical processes, not, save a metaphor, certain types of motion of information. [22]

However, this reasoning assumes that there is no possible solution to the Grandfather Paradox, and that the possibility of sending a message into the past necessarily raises the danger of inconsistency, which will be addressed in the following section.

## 2.5 Nonlocal Signaling

The failure of continuity in the kinds of models Gisin had in mind does not entail an inability to signal. As Timpson described in his analysis of teleportation, QIT arguably requires that we drop the Principle of Continuity when modeling the information manipulation capabilities of quantum systems.

In combination with the argument from Section 2.3 about signaling's consistency with relativity, the adoption of the non-continuous model of the influences of quantum entanglement lead us to a particular understanding of signaling. This I will term Nonlocal Signaling (NS). It is the communication allowed by a SD, the operation of which cannot be explained by a $v$-causal model. In NS, there is no carrier of information physically traversing the space between the two communicating parties. Rather, the input on Alice's side causes Bob's output purely nonlocally.

The synthesis of Gisin's argument that superluminal causal influence is not inconsistent with relativity, provided we assume a privileged reference frame in which the definite causal order is defined, with Timpson's argument that a failure of the Principle of Continuity is not inconsistent with a well-defined physics, leads us to a picture of superluminal signaling with the following features:

- A Signaling Device can, with some probability, send a message from Alice to Bob

- The signal need not be continuously carried through the space between Alice and Bob (the Principle of Continuity does not hold).

- There is some privileged reference frame in which the speed of the signal takes on a maximum value $v$ (possibly allowing for instantaneous transmission).

Importantly, the constraint on superluminal travel from special relativity is distinct from—and does not entail—a prohibition against signaling via the exploitation of quantum nonlocality. But what about the worries raised by Timpson and others of temporal paradox? Nielsen and Chuang fall just short of saying that relativistic considerations make signaling impossible, referring to it instead as an "apparent paradox":

> First, doesnt teleportation allow one to transmit quantum states faster than light? This would be rather peculiar, because the theory of relativity implies that faster than light information transfer could be used to send information backwards in time. Fortunately, quantum teleportation does not enable faster than light communication, because to complete the teleportation Alice must transmit her measurement result to Bob over a classical communications channel. [...] The classical channel is limited by the speed of light, so it follows that quantum teleportation cannot be accomplished faster than the speed of light, resolving the apparent paradox. [23]

The unrestricted ability to signal faster than light allows for the transmission of information to the past by relaying information superluminally first from Alice, who is at rest, to Bob, who is in motion. If Bob can send the information back to Alice faster than light with respect to *his* frame, it is possible for the message to reach Alice's past.

Gisin's imposition of a privileged reference frame has the potential to solve the problem. If the transmission of information at $v$ can only occur in Alice's frame, then the speed of the signal that Bob can return to Alice, with respect to his own frame, will be significantly slower than $v$, such that no message to the past will be allowed.

However, the model on which the SD that will be developed in the following chapter is based does not include a privileged reference frame. Rather, it has another way of preventing temporal paradoxes. Deutsch's consistency condition explicitly rules out histories in which contradictions occur, making his many worlds safe for historians.[4]

I've argued that relativistic considerations are not directly relevant to the possibility of superluminal signaling in quantum theory. Maudlin has developed some exotic models that are consistent with relativity in which superluminal causal influence exists. Gisin showed that our current theoretical and experimental understanding of quantum theory is consistent with the existence of superluminal signaling, provided there exists a privileged reference frame. Timpson argued that quantum information transmission should be understood as a discontinuous process in certain cases. He argues that signaling must fail on pain of the Grandfather Paradox.

Therefore, a discontinuous instantaneous signal constrained to a privileged ref-

[4]Bub and Stairs in [41] consider the information Alice can send to her own past via the relay system described above to be in the classical domain, and therefore not subject to Deutsch's consistency condition, which they interpret as applying only to quantum information. I address this argument in Chapter 3.

erence frame is not inconsistent with relativity. Nor is a discontinuous instantaneous signal that is constrained by a temporal consistency condition, in order to ensure that no contradiction can obtain.

I propose that we adopt a distinction between superluminal transfer of information (FTLIT), in which a carrier of information traverses the space between the two distant regions faster than a light signal could, and Nonlocal Signaling (NS), which relies on nonlocal quantum effects, and in which no information carrying system traverses the intermediate space.

It is conceptually possible for one to exist without the other. After all, we could discover that $c$ is not the maximum speed for material particles, without having to invoke quantum effects. And it was an open question as to whether the quantum correlations precisified in Bell's Theorem would allow for the transmission of messages. As Timpson argued, the quantum formalism itself does not require that there be carrier particles responsible for the nonlocal effects. If this were not the case, the existence of the ordinary non-signaling quantum correlations seems to already be enough to be in conflict with relativity. If we assume that the correlations between the distant measurements must be explained by the transmission of a causal influence through spacetime, then the correlations allowed by ordinary quantum theory already seem to come into conflict with relativity. It is often argued that this is not the case, since the superluminal causal influence traveling between the two distant regions does not result in any epistemically relevant experimental outcome. That is to say, Bob cannot discover Alice's input based on his output, even though a superluminal causal influence has traveled to him from Alice's experimental setup, causing him to get the particular outcome he does. However, if this is the reason that ordinary quantum correlations are not in conflict with relativity, then information is playing an important role here. The prohibition seems to be weakened to the point where it is no longer that nothing can travel faster than light (in fact, causal influence can, so long as it has no noticeable effect). What is prohibited from traveling faster than light is usable information (see e.g. [34] [30]).

Although ordinary quantum mechanics rules out signaling, a simple extension of the theory induced by the existence of a localized region of non-linearity, predicts that signaling does occur. This effect is purely quantum mechanical, and, for the reasons detailed above, does not conflict with relativity, despite arguments to the contrary. It is to this extension of quantum theory that we now turn.

# Chapter 3: Would the Existence of CTCs Allow for Nonlocal Signaling?

## 3.1 Introduction

QIT has been a majorly productive research program over the last two decades. It has enabled scientists to make progress theoretically, experimentally, and in terms of the development of technology. However, our understanding of what quantum information is telling us about the world—and what it is telling us about quantum theory itself—remains underdeveloped. Broadly speaking, this paper is an attempt to reconcile the conceptual framework at play in the metaphysical approach to the foundations of quantum mechanics with the framework at play in quantum information science.

In this paper, I focus on a debate about the predicted behavior of quantum systems in the presence of a localized region of spacetime subject to nonlinear laws of evolution. The particular example under consideration is that of a closed timelike curve, or CTC. In this literature, the peculiarities of how time travel could possibly be achieved are not addressed. Rather, CTCs are treated as a resource. In this context, we can formulate the question "what could we do if we had access to a

CTC?"

David Deutsch's seminal 1991 paper [1] set the groundwork for a quantum mechanical analysis of the information-processing capabilities of a quantum system augmented by access to a CTC. Over the last decade, interest has flourished in the particular computational tasks that can be achieved with a CTC-assisted quantum computer circuit. However, a debate has arisen surrounding a particularly strange result: the ability to distinguish non-orthogonal quantum states. This is impossible according to ordinary quantum theory, but the Deutsch's analysis of the behavior of quantum systems in the presence of a CTC seems to predict it.[1] Furthermore, this ability leads to an even more radical conclusion: quantum CTCs allow for information to be sent between arbitrarily distant parties instantaneously.

However, there has been serious resistance to this conclusion from various parties to the debate. And the attempts to formulate exactly why this admittedly non-quantum-mechanical behavior should be ruled out has illuminated the underlying assumptions that are often at play, even in a field such as quantum information, which purports to be formulated entirely in operationalist terms, and neutral with respect to interpretational debates.

A CTC-assisted quantum computational circuit may seem like an exotic example. But analyzing these kinds of systems has proved to be very fruitful. Working with this example has brought to light several common confusions about one of

[1] In this paper, I will be working exclusively with Deutsch's CTC model for quantum systems (D-CTCs). There is an alternative proposal for how to understand the behavior of quantum systems in the presence of CTCs, referred to as P-CTCs. While there are significant differences between the predictions and underlying physics of the two proposals, both allow for the behavior under consideration in this paper, i.e. distinguishing non-orthogonal states, and Nonlocal Signaling. In fact, Gisin showed [42] that a more general nonlinear framework would allow for the same behavior.

the central concepts of quantum theory: nonlocality. In the foundations literature, quantum nonlocality is often closely connected to the concepts of information and causation. For example, it is often said that the nonlocal correlations of quantum mechanics are allowed at spacelike separation because no information is traveling between the two distant systems $A$ and $B$ faster than a light signal could. In cases where nonlocality is exploited as an information channel (as in the quantum teleportation protocol) then quantum information is not present (or useable) at $B$ until after a classical (lightlike) signal is received from $A$.

I will argue that the exploitation of quantum correlations to send a message—as allowed by the existence of CTCs—should be distinguished from cases where a carrier of information is physically traversing the space between two distant points faster than the speed of light. These two notions are often conflated. Insofar as relativity prevents any material particle from traveling through space faster than light, it prohibits only the latter, and does not rule out the possibility of (what I term) Nonlocal Signaling.

This is contrary to a foundational principle of the quantum information-theoretic approach. The No-Signaling Principle plays a fundamental role in the formulation of quantum information. I argue that this accounts for the resistance to the conclusion that it can be violated under certain conditions. Furthermore, I argue that the No-Signaling Principle's inclusion as a fundamental postulate about the nature of the quantum world, as is the case in the quantum information-theoretic interpretation of quantum theory, as advocated in Bub and Pitowsky's "Two Dogmas About Quantum Mechanics", represents a commitment to a principle-theoretic conception of quantum theory.

Whereas a "constructive" theory is built up from its ontology and dynamics, the fundamental formulation of a "principle" theory is "top-down", in terms of inviolable global principles (the paradigm case is special relativity). Principle theories explicitly deny the fundamentality of a theory's ontology, and consider constructive formulations of theories to be secondary, and to have a role only as proofs of the consistency of their principles.

This paper will examine the recent debate surrounding this point in the foundations literature. I will address each argument for the impossibility of Nonlocal Signaling. I will argue that each of these arguments falls short of its goal either for technical reasons, or for reasons of insufficient justification for imposing global constraints on the possible correlations allowed in this context.

I will argue that there is a deeper motivation at play for ruling out the possibility of Nonlocal Signaling, which has to do with the fundamental commitments of the quantum information approach. I argue, however, that the framework developed by Deutsch is inconsistent with these commitments, and therefore the justification for including a No Signaling principle in the D-CTC framework offered by quantum information theorists is indefensible.

## 3.2 Deutsch's Circuit Model for CTCs

In his well known 1991 paper [1], Deutsch introduced a model for the analysis of the physical behavior of CTCs. Prior to his work, the standard way of analyzing the physical effects of chronology-violating regions of spacetime was in terms of their underlying geometry. Deutsch considered this approach to be insufficient because it fails to take quantum mechanical effects into account. He proposed an alternative approach which involves analyzing the behavior of CTCs in terms of their information processing capabilities.

He begins his account by defining a notion of equivalence between spacetime-bounded networks containing chronology-violating regions. A network in this context is to be understood as a spacetime geometry which takes as input the initial state of a physical system and outputs the system's final state. Two networks are *denotationally equivalent* if their outputs are the same function of their inputs. That is to say, regardless of whether two networks have differing spacetime geometries, if the function that maps their initial states to their final states is the same, they are denotationally equivalent.

Next he introduces the idea that the transformation between any two denotationally equivalent networks is trivial. Insofar as we are interested in analyzing CTCs in terms of their physical effects (that is, their output given a certain input), we are free to use the simplest model available in the denotational equivalence class of a particular network for the purpose of our analysis of the information flow through a CTC.

The final step of his proposal is to introduce a simple standard form into which any spacetime-bounded network can be trivially transformed for the purpose of analysis. The simple standard form involves translating all spacetime-bounded networks into circuits in which each particle traveling in the original network is replaced by sufficiently many carrier particles, each of which have a single 2-state internal degree of freedom (a bit). The regions in which the particles interact are localized (by denotationally trivial transformations) into gates, such that the particles are inert while traveling between them. And finally, all chronology-violating effects of the network are localized to sufficiently many carrier particles on closed loops, which only interact with chronology-respecting particles in gates.

Deutsch points out that chronology violation itself makes no difference to the behavior of a network unless there is a closed loop of information. In the original network, this closed information path could potentially not be confined to the trajectory of any single particle (since the carriers can interact with each other), but for any such network, there is a denotationally trivial transformation which will localize the closed information path on sufficiently many carriers on closed paths.

The real innovation of this approach is that it can very easily accommodate quantum mechanical effects by relaxing the requirement that the carrier particles be in a well-defined classical state after interactions. If viewed classically, networks containing chronology violations can lead to paradoxes that seem to put unnaturally strong constraints on possible initial conditions of physical systems (e.g. you are somehow prohibited from getting in the time machine that would take you back to kill your grandfather). Deutsch uses his model to argue that, when quantum mechanics is taken into account, these unnatural constraints on initial states disappear. Deutsch's fixed point theorem states that CTCs "place no retrospective constraints on the state of a quantum system" [1]. That is to say, for any possible input state, there will be a paradox-free solution.

This is the result of a consistency condition implied by the quantum mechanical treatment of time-traveling carrier particles interacting with later versions of themselves. If we let $|\psi\rangle$ be the initial state of the "younger" version of the carrier particle, and let $\hat{\rho}$ be the density operator of the "older" version of the carrier particle, then the joint density operator of the two particles entering the region of interaction is

$$|\psi\rangle\langle\psi| \otimes \hat{\rho}$$

and the density operator of the two carrier particles after the interaction is

$$U(|\psi\rangle\langle\psi| \otimes \hat{\rho})U^{\dagger}$$

where $U$ is the interaction unitary. The consistency condition requires that the density operator of the younger version of the carrier particle as it leaves the region of interaction is the same as that of the older version as it enters the region of interaction.

This makes intuitive sense, because it is the interaction that causes the earlier version of the carrier particle to become the later version. When translated via a denotationally trivial transformation to a network in which the chronology-violating behavior is localized to a single particle on a CTC that interacts with a chronology-respecting (CR) carrier particle, the consistency condition for the CTC system is

$$\rho_{\mathrm{CTC}} = \mathrm{Tr}_{\mathrm{CR}}[U(|\psi\rangle\langle\psi| \otimes \rho_{\mathrm{CTC}})U^{\dagger}].$$

This requirement says that, after tracing out the CR qubit, the density operator of the system on the CTC *after* the interaction is the same as it was *before* the interaction. That is to say, after the interaction, the carrier particle on the CTC enters the "future mouth" of the wormhole, and exits the "past mouth" of the wormhole *before* the interaction. The state of the particle that comes out of the past mouth must be the same as the system that enters the future mouth. Furthermore, $\rho_{\text{CTC}}$ depends on $|\psi\rangle$, so the input state on the causality-respecting carrier particle has an effect on the state of the particle it will interact with.

The output of the circuit (i.e. the final state of the CR qubits) depends on the input of system $|\psi\rangle$ and $\rho_{\text{CTC}}$. And, as we see in the previous equation, $\rho_{\text{CTC}}$ itself depends on $|\psi\rangle$. Therefore, the evolution of the CR qubit is nonlinear with respect to the input $|\psi\rangle$.

$$\rho_{\text{output}} = \text{Tr}_{\text{CTC}}[U(|\psi\rangle\langle\psi| \otimes \rho_{\text{CTC}})U^{\dagger}]. \tag{3.1}$$

Whatever the physical situation is, its information flow can be redescribed in a form that has the following features: There are a finite number of qubits bound to a CTC. These interact via unitaries with a finite number of qubits that follow an ordinary chronology–respecting trajectory. The CR qubits are measured after their interaction with the CTC qubits, and their state is the final state of the system. In the region of interaction, the CTC qubits behave according to ordinary quantum mechanics, and interact with the CR qubits via unitary interactions. The CTC qubits do not evolve in any way while traveling back along the CTC. The nonlinearity of the systems overall evolution is entirely due to the consistency conditions nonlinearity.

This means that the closed information loops of chronology violation can be isolated into localized regions of spacetime. The effects that can be generated by interaction with the CTC can range over all of space, of course. But they must be the result of entanglement, or prior causal interaction, with systems in the region of interaction with the chronology violating qubits.

In light of the model's reliance on this nonlinear consistency condition, Deutsch's claim that CTCs, when properly understood, place no constraints on the possible states of the quantum system may be stronger than is warranted. While it is true that, unlike the classical analysis of time travel paradoxes, his model places no constraints on the input state of the causality-respecting system, it *does* constrain the possible states of the system confined to the CTC.

While Deutsch's solution seems more intuitively plausible than the constraint on initial conditions that prevents the occurrence of classical time travel paradoxes, it is nonetheless puzzling. In the classical case, it is somehow forbidden that I get in the time machine that will take me back to kill my grandfather. There isn't necessarily any obvious causal mechanism that prevents me. It is simply impossible, to avoid paradox, that I ever actually carry out my mission. This constraint is often described as *superdeterministic*, since it is something above and beyond simple determinism that rules out the possibility of me getting into the time machine. David Lewis's influential formulation of the classical consistency condition from his [19] alleviates some of this tension by redescribing the time travel narrative as a single, self-consistent history. The drawback of this approach is that it seriously undermines the notion that the time traveler has free will.

Deutsch characterizes his problem with the classical solutions as stemming from the fact that they violate what he calls the *principle of autonomy*.

> According to this principle, it is possible to create in our immediate environment any configuration of matter the laws of physics permit locally, without reference to what the rest of the universe may be doing. [43]

He claims that classical solutions to the Grandfather Paradox, which impose global consistency, violate this principle.

> Under this principle, the world outside the laboratory can physically constrain our actions inside, even if everything we do is consistent, locally, with the laws of physics. Ordinarily we are unaware of this constraint, because the autonomy and consistency principles never come into conflict. But classically, in the presence of CTCs, they do. [43]

In Deutsch's model, this tension is seemingly resolved. Any initial state of the system is allowed—the time traveler could enter the time machine with any intentions whatsoever. Consistency is guaranteed by the state of the system confined to the CTC. This doesn't offend the intuitions as badly as the classical case, because we can imagine the following "pseudo–time" narrative: The causality-respecting qubit begins its journey in some initial state, then encounters and interacts with CTC qubit, precipitating a change of state of both of them. The CTC qubit in its new state then travels back in time to again interact with the causality-respecting qubit (in its initial state), and the interaction again changes the state of the CTC qubit. Over infinite iterations of this process, the CTC qubit converges on some particular state, like the rotation of a top stabilizes after some initial wobbling. The CR qubit *causes* the CTC qubit to be in the right state.

The puzzle arises, though, when we note that the CTC qubit must *always* have been in this stable state. There are no previous interactions with the CR qubit to force it to evolve over time into the right state. So although Deutsch's model has avoided the superdeterminism of the traditional time travel paradoxes, which constrained the initial states of the CR system, it seems to have introduced significant kinematic constraints in another place. Something like Lewis's classical consistency condition must still be at play. That is to say, there must be a deeper metaphysical justification (i.e. the impossibility of a self-contradictory history) which is behind Deutcsh's quantum condition. And as we'll see in Section 5.2, Deutsch seemingly has something like this in mind.

Deutsch's analysis of the physical effects of chronology-violating regions of spacetime in terms of quantum computational circuits and the consistency condition has been very influential in the study of quantum information, and has led to many interesting insights about the nature of the quantum world. One particularly interesting result is due to Brun, Harrington and Wilde. In what follows, I will discuss their work, the debate surrounding their central claim, and further implications of their argument.

## 3.3 The BHW Circuit

In [18], the authors described a procedure for using CTC-assisted quantum computational circuits to distinguish between non-orthogonal states of a qubit. In this section, I will describe the protocol for distinguishing between the linearly depenent BB84 states $|0\rangle$, $|1\rangle$, $|+\rangle$ and $|-\rangle$, where $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ and $|-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$.

### 3.3.1 Details of the BHW Circuit

The authors begin by detailing a protocol for distinguishing between two non-orthogonal states. The setup involves two qubits: system $A$ in the unknown initial state $|\psi\rangle$ (either $|0\rangle$ or $|-\rangle$), and system $B$, a qubit in some state $\rho_{\text{CTC}}$ on a CTC. The procedure is simple: (1) perform a SWAP of systems $A$ and $B$, (2) perform a controlled-Hadamard transformation with system $A$ as the control and system $B$ as the target, and (3) measure system $A$ in the computational basis. A measurement of system $A$ that yields the output $|0\rangle$ means that the input state is $|\psi\rangle = |0\rangle$. A measurement of system $A$ that yields the output $|1\rangle$ means that the input state is $|\psi\rangle = |-\rangle$.

This result obtains because of Deutsch's consistency condition. Whatever state system $B$ is in when it enters the future mouth of the wormhole must be the same state that comes out of the past mouth of the wormhole. That is, steps (1) and (2) must have no net effect on system $B$. The density matrix of the system on the CTC (system $B$) depends on the input state of system $A$:

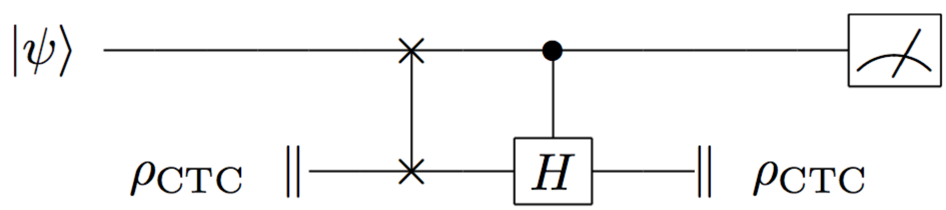
$$\rho_{\text{CTC}} = \text{Tr}_{\text{CR}}[U(|\psi\rangle\langle\psi| \otimes \rho_{\text{CTC}})U^{\dagger}]$$

and the output of the circuit (i.e. the final state of the CR qubit) depends on the input of system $A$ and $\rho_{\text{CTC}}$:

$$\rho_{\text{output}} = \text{Tr}_{\text{CTC}}[U(|\psi\rangle\langle\psi| \otimes \rho_{\text{CTC}})U^{\dagger}].$$

Since the only two possible input states are $|\psi\rangle = |0\rangle$ and $|\psi\rangle = |-\rangle$, the consistency condition requires that the only possible initial states of system $B$ are $\rho_{\text{CTC}} = |0\rangle\langle 0|$ and $\rho_{\text{CTC}} = |1\rangle\langle 1|$.

Figure 3.1: BHW circuit for distinguishing between $|\psi\rangle = |0\rangle$ and $|\psi\rangle = |-\rangle$ (from Brun et al. 2009).




Consider the situation where the input state of system $A$ is $|\psi\rangle = |0\rangle$. If the initial state of system $B$ is $\rho_{\text{CTC}} = |1\rangle\langle 1|$, then the effect of the first gate ($SWAP$) would be to transform system $A$ into the state state $|1\rangle$ and system $B$ into the state $|0\rangle$. Since system $A$ is in the state $|1\rangle$, the action of the second gate (controlled-Hadamard with $A$ as the control and $B$ as the target) would transform system $B$ into the state $|+\rangle$. Since the consistency condition requires that the state of $B$ after the action of the two gates is the same as the state of $B$ before the action of the two gates, it is clear that $\rho_{\text{CTC}} = |1\rangle\langle 1|$ is not an allowed initial state of system $B$ when $|\psi\rangle = |0\rangle$.

However, if the initial state of system $B$ were $\rho_{\text{CTC}} = |0\rangle\langle 0|$, then after the action of the first gate ($SWAP$), system $A$ would be in state $|0\rangle$ and system $B$ would be in state $|0\rangle$. The second gate (controlled-Hadamard) would not be activated since the control qubit is in state $|0\rangle$, so the consistency condition for system $B$ holds. The measurement of system $A$ would yield a result of $|0\rangle$, which indicates that the initial input state was $|\psi\rangle = |0\rangle$.

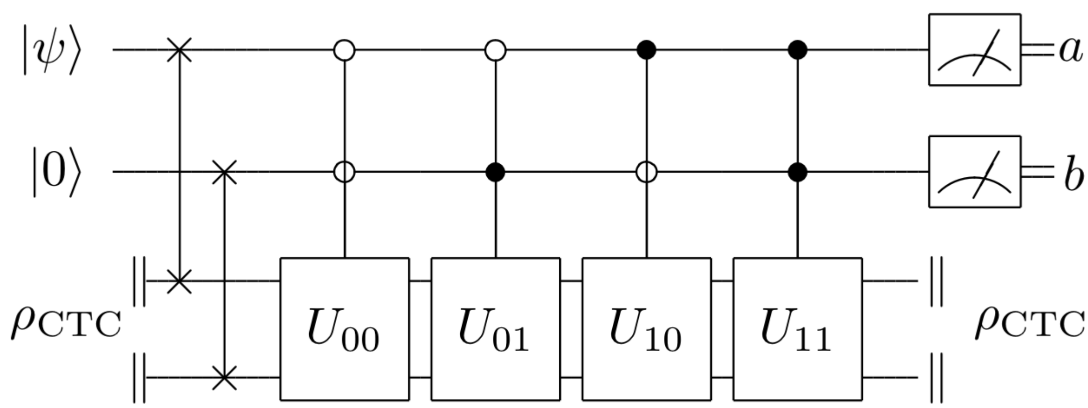
Now consider the case where system $A$ is initially in the state $|\psi\rangle = |-\rangle$. If the initial state of system $B$ is $\rho_{\text{CTC}} = |0\rangle\langle 0|$, then after the action of the first gate ($SWAP$), system $A$ would be in the state $|0\rangle$ and system $B$ would be in the state $|-\rangle$. Since $A$ is the control qubit for the second gate (controlled-Hadamard), it would not be activated and system $B$ would pass through unchanged. It would therefore enter the future mouth of the wormhole in the state $|-\rangle$, violating the consistency condition.

However, if system $B$ had initially been in the state $|1\rangle$, after the first gate, system $A$ would be in the state $|1\rangle$ and system $B$ would be in the state $|-\rangle$. The control qubit would activate the controlled-Hadamard gate, and system $B$ would be transformed into the state $|1\rangle$, which is consistent with its original state. The measurement on system $A$ will yield a result of $|1\rangle$, which indicates that the input was initially $|\psi\rangle = |-\rangle$.

Brun and his collaborators were able to scale this protocol up to allow for the discrimination between the four non-orthogonal BB84 states $|0\rangle$, $|1\rangle$, $|+\rangle$ and

$|-\rangle$. They achieve this by adding an ancillary chronology-respecting qubit in the state $|0\rangle$, using two CTC-bound qubits, performing two SWAPs and four controlled unitary transformations, and making two measurements.

Figure 3.2: BHW circuit for distinguishing the four BB84 states (from Brun et al. 2009).




The unitary transformations are as follows:

$$U_{00} \equiv SWAP$$
$$U_{01} \equiv X \otimes X$$
$$U_{10} \equiv (X \otimes I) \circ (H \otimes I)$$
$$U_{11} \equiv (X \otimes H) \circ (\text{SWAP})$$

The circuit performs the following map ($|\psi 0\rangle \to |ab\rangle$):

$$|00\rangle \to |00\rangle$$
$$|10\rangle \to |01\rangle$$
$$|+0\rangle \to |10\rangle$$
$$|-0\rangle \to |11\rangle$$

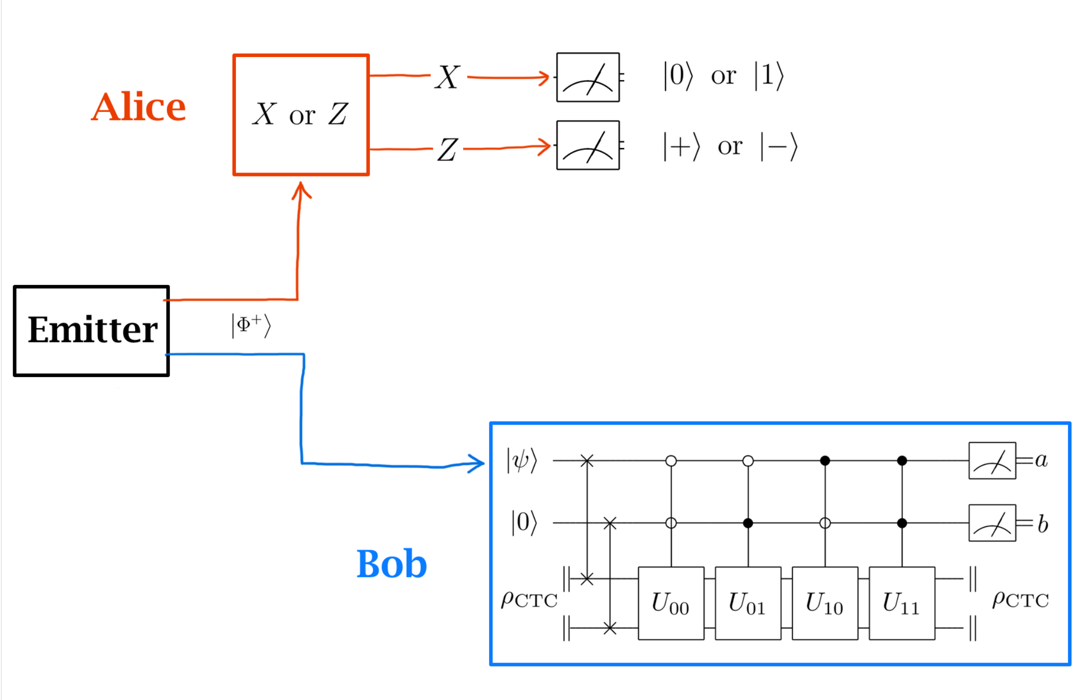
### 3.3.2 Using BHW to Signal

In Cavalcanti et al.'s [29], the authors point out that the evolution of the quantum state through the BHW circuit which allows for the possibility of distinguishing the BB84 states is of the right kind to fit into a protocol for instantaneous signaling proposed by Gisin [42].

Gisin's proposal involves two players, Alice and Bob, each sharing one half of a singlet pair. Alice measures her particle either in the $X$ direction (yielding $|1\rangle$ or $|0\rangle$) or the $Z$ direction (yielding $|+\rangle$ or $|-\rangle$), forcing Bob's particle into the same state. Bob then subjects his particle to a nonlinear evolution of a certain type that allows him to determine its state. Gisin proposed a particular nonlinear Hamiltonian that would do the job, but Cavalcanti and Menicucci point out that the BHW circuit has the right features to fit into this framework.

The BHW circuit will allow Bob to perfectly distinguish between all four states. Therefore, if Alice wants to send a 1-bit message, she can choose either to measure in the $X$ direction (for "yes") or the $Z$ direction (for "no"). Bob, using the BHW circuit, can recover Alice's message, which is transmitted instantaneously. That is, if the output of Bob's device is $|10\rangle$ or $|11\rangle$, he knows Alice measured her half of the singlet pair in the $X$ direction (intending the message to be "yes"), and if his results are either $|00\rangle$ or $|01\rangle$, he knows she measured in the $Z$ direction (meaning "no").

Figure 3.3: Cavalcanti and and collaborators' proposal for using the BHW circuit in Gisin's instantaneous signaling device. Alice measures first measures her particle along the $X$ or $Z$ axis. Bob then uses the BHW circuit to determine what state his particle is in.




### 3.3.3 The Bub-Stairs Consistency Condition

In a recent paper [41] Jeffrey Bub and Allen Stairs propose a consistency condition to solve one of the outstanding conceptual problems with Nonlocal Signaling. Their condition solves some potential ambiguity associated with the possibility of signaling.

The issue that the consistency condition is designed to solve arises because of the fact that the nature of Nonlocal Signaling allows for cause/effect to happen at spacelike separation. Alice's choice of measurement causes Bob to get the result he does faster than a light signal would have been able to traverse the distance. Since the event of Alice's input and the event of Bob's output are at spacelike separation, observers in different frames will disagree about which event comes before the other.That is, for some observers, Bob will measure his particle before Alice measures hers. In those frames, Alice and Bob's shared Bell State will not have been disentangled by Alice's measurement, and therefore Bob will input a particle in the state $I/2$ into the BHW circuit, which will yield any of the four possible outcomes with equal probability, meaning that he has a 1/2 probability, in that frame, of getting an output that corresponds to the wrong input for Alice. In frames where Alice measures first, her choice determines Bob's output by disentangling their shared Bell State, leading to Bob measuring a particle in a definite state with the BHW circuit. In frames where Bob measures first, he inputs his still-entangled particle into the BHW circuit, yielding each of the four possible outputs with equal probability, regardless of the input Alice later chooses.

To protect against this sort of problem, they introduce a simple and elegant new consistency condition. It consists of the conjunction of the following two claims:

(C1) Observers in differently moving reference frames agree on which events occur, even if they disagree about the order of events.

(C2) If an event has zero probability in any frame of reference, it does not occur.

C1 ensures the two observers would agree about the outcomes of the two measurements (namely that the output Bob gets corresponds to the input Alice makes, regardless of who goes first). C2 ensures that the contradiction will never arise, since according to one observer, the probability of Bob getting the outcome that is inconsistent with Alice's input is 0.

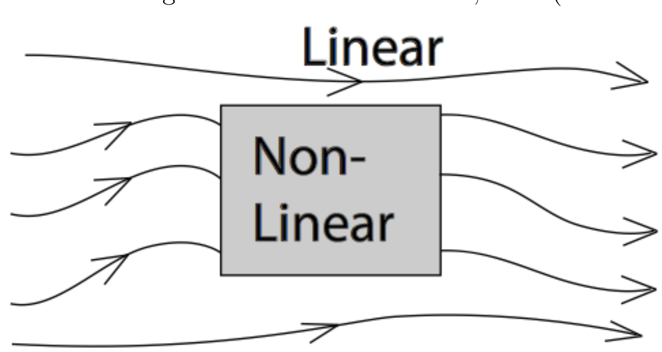
While the consistency condition seems unobjectionable, I'll argue in Section 5.3 that the conclusions Bub and Stairs attempt to draw from it are more problematic.

## 3.4 Signaling and Relativity

### 3.4.1 The Preparation Problem

Cavalcanti and his collaborators argue against the possibility of signaling by questioning the assumption that different preparation procedures, which yield the same state in the context of ordinary quantum mechanics, will continue to do so in this more general extension of the theory. They claim that superluminal signaling is ruled out by special relativity, and we should therefore conclude that something has gone wrong in the argument that led us to predict this effect. They begin by defining a notion of a nonlinear extension of quantum mechanics that reduces to ordinary quantum mechanics everywhere outside of a particular spacetime region. That is, they describe an ordinary quantum world, with one localized extraordinary region, where the output states are a nonlinear function of the input states. They refer to this region as the "nonlinear box".

Figure 3.4: A localized region of nonlinear evolution, from (Cavalcanti et al. 2012).



According to Deutsch's model, the effects of the existence of a CTC can be localized to a particular region by a denotationally trivial transformation, so locating all of the effects of a CTC in a nonlinear box is allowed. In this model, standard linear quantum mechanics is true everywhere outside the box, and the only nonlinear evolutions happen to systems inside the (or traveling through) the box.

In order to block the failure of the No Signaling principle, they argue that different preparation procedures that unproblematically yield the same pure state according to linear quantum mechanics, will in fact yield different states, which will have different effects in the context of this nonlinear extension of quantum theory. Specifically, even though we consider the following two preparation procedures to yield the same pure state in linear quantum mechanics, the equivalence fails in the theory including the nonlinear box:

**Procedure 1** Measure the an ensemble of qubits in the computational basis, and post-select those that are in the state $|1\rangle$.

**Procedure 2** Take an ensemble of pairs of maximally entangled qubits in the Bell state $|\Phi^+\rangle$, and measure the states of the $A$ qubits in the computational basis, then post-select the $B$ qubits that were entangled with the $A$ qubits for which the measurement result was $|1\rangle$.

As Cavalcanti and his collaborators say:

> Signaling can be avoided *only if* the remote preparations in [Procedure 2] are not in the same equivalence class as the corresponding preparations in [Procedure 1] when nonlinear transformations are considered. [29]

But this prescription leads to what they call the "preparation problem", which has two parts. Firstly, if it is the case that a pure quantum state does not uniquely determine a system's evolution through a nonlinear box (because it may be the result of either preparation procedure), then the formalism of quantum states seems to be insufficient to account for the physical situation. Secondly, the model is incomplete without a specification of which preparation procedures fall into which equivalence classes in the nonlinear box.

### 3.4.2 Reply to Cavalcanti

Cavalcanti et al. argue that, since instantaneous signaling is impossible, something must have gone wrong with the analysis of the BHW circuit that led to the prediction that Alice could send a signal to Bob.

> Under these assumptions, Alice may send information to Bob instantaneously. Since consistency with relativity forbids this, we must rethink our assumptions. [29]

In this section I will argue that the constraint on superluminal travel from special relativity is distinct from—and does not entail—a prohibition against signaling via the exploitation of quantum nonlocality.

As I argued in Chapter 2, Nonlocal Signaling, which exploits quantum phenomena to send instantaneous signals, is not necessarily in conflict with relativity. In the context of this debate, the D-CTC mode's consistency condition is sufficient to protect against any causal–ordering paradoxes that seem to the threaten the consistency of NS with SR.

Given that the Cavalcanti et al. paper is participating in this very debate, and given that the argument most frequently made on relativistic grounds against the possibility of signaling is that it would allow for messages to the past, we can take Timpson's analysis of the transmission of information from $A$ to $B$ to undermine Cavalcanti's stated justification for ruling out the possibility of signaling.

The distinction proposed in Chapter 2 that we adopt a distinction between superluminal transmission of information (FTLIT), in which a carrier of information traverses the space between the two distant regions faster than a light signal could, and Nonlocal Signaling (NS), which relies on nonlocal quantum effects, and in which no information carrying system traverses the intermediate space is helpful for disentangling the quantum implications from the relativistic commitments.

It is conceptually possible for one to exist without the other. The quantum formalism itself does not require that there be carrier particles responsible for the nonlocal effects. If we assume that the correlations between the distant measurements must be explained by the transmission of a causal influence through spacetime, then the correlations allowed by ordinary quantum theory would already be in conflict with relativity.

To summarize, if the concern with the BHW signaling protocol is that something (a causal influence, say) is traveling faster than the speed of light, then the teleportation protocol should already have given Cavalcanti et al. pause. Both the signaling and the teleportation protocol share the feature that the information appears at $B$ instantaneously after being sent from $A$.

I contend that the problem lies elsewhere. This can be illustrated by the implausibility of the following scenario assuaging any of their concern: Alice uses the BHW signaling setup to send a message to Bob, but Bob waits to make his measurement (and therefore receive the message) until after a light signal could have potentially traversed the space between them, even though no such signal was sent.

This hypothetical scenario is actually similar to the teleportation protocol in one important respect: even though Bob's system is instantaneously affected by Alice's choice of measurement, the information isn't present at $B$ until after enough time has elapsed to ensure that no information was transmitted faster than the speed of light. Of course, in our imagined scenario, this feature is purely accidental, whereas in the teleportation protocol, this feature is necessary.

The important differences between teleportation and signaling are two. Firstly, what is sent to Bob in the teleportation protocol is an unknown quantum state, and therefore not information he can *use*. Secondly, the token of the information isn't actually produced at Bob's location until after two classical bits of information are sent through a classical (subluminal) channel. (One in four times, however, that information tells Bob that he already has the correct state in hand. In those cases, even though the target state has already been reproduced, he doesn't have verification of this fact until the classical bits arrive. This is a good example to draw out the fact that the exploitability of the information is what is being prevented in teleportation.) These two features prevent the teleportation protocol from being used to send signals.

With respect to Cavalcanti et al.'s argument, I'll simply say that the nonlinear evolution from which they were generalizing in their paper (and which is the only one to have been explicitly shown to allow for signaling) is that generated by the presence of a CTC, which explicitly allows for information to be sent to the past, and which has a feature (namely, the consistency condition) that protects against temporal paradoxes.

However, even in the absence of the relativistic justification for ruling out the impossibility of instantaneous signaling, Cavalcanti et al. would likely still want to rule it out on other grounds. If they can establish that instantaneous signaling is in principle impossible, then their argument that "we must rethink our assumptions" in our analysis of the BHW circuit would go through.

In the following section, I'll examine why this may be. I argue that the impossibility of Nonlocal Signaling is a fundamental principle of quantum information, and the project of an information-theoretic interpretation of quantum theory relies on the exceptionless truth of such principles. The reason for this is a deep difference in the conception of physical theories between the proponents of the quantum information perspective, and those who consider the ontology of a theory to be among its most fundamental elements.

## 3.5 Quantum Information-Theoretic Motivations

### 3.5.1 Why Maintain No Signaling?

I've argued that the relativistic justification for the No-Signaling Principle doesn't stand up to scrutiny. I will argue that the reason for the reticence to give up the No-Signaling Principle has to do with its status in the QIT. In particular, it is one of the most promising principles used in the reconstructions of quantum theory from the space of generalized probabilistic theories. This research project considers the space of all possible theories formulated in terms of their information processing capabilities and their allowed correlations between events.

> For any theory, whether it applies to Nature or not, one can consider the information processing possibilities of this theory, the differences from those of classical or quantum theory, and attempt to trace these possibilities back to the fundamental features of the theory. [44]

Principles are introduced, which partition the theories in that generalized theory space. The hope is that a small number of physically plausible principles can be identified which will pick out exactly those correlations allowed by quantum theory. On this view, these principles would give us an answer to the question of why our world allows for the quantum correlations to obtain, and not others.

No Signaling is one of the core principles at the heart of this approach. It is taken to be one of the most physically plausible candidates for a foundational principle of quantum theory. If the privileged status of the No Signaling principle were to be undermined, that would in turn undermine the status of other principles promising for this project, which live or die with No Signaling. One such example is the principle of "information causality", which generalizes the No Signaling principle in the following way. If Alice sends Bob $m$ classical bits, the most classical information Bob can extract from that message is $m$ bits. This reduces to the No Signaling principle in the case where $m = 0$ [45]. This is consistent with the teleportation protocol because, even though Alice can send Bob a quantum state that would take a potentially infinite amount of classical information to perfectly specify, Bob cannot extract more than the 2 classical bits Alice sent to him. Having Alice's input state $|\psi\rangle$ in hand does not give Bob any more information.

This approach is closely associated with the principle-based conception of physical theories. This is a conception in which the fundamental formulation of a physical theory is in terms of principled restrictions on the kinematical level. These principles never need to be justified by ontological or dynamical considerations. An empirically equivalent theory theory formulated in terms of dynamics and ontology is taken on this approach to represent a less fundamental formulation.

The special theory of relativity is taken to be the paradigm example of this kind of theory. Just as the Principle of Relativity and the Light Postulate pick out Minkowski spacetime as the space of events in SR, and constrain the structure of events in spacetime, the information-theoretic interpretation of quantum theory take there to be principles that define a space of events for quantum theory, and that space to constrain the structure of those events. As Bub and Pitowsky say in their articulation of QITI:

> In the case of quantum mechanics, these principles are information-theoretic and include a 'no signaling' principle and a 'no cloning' principle. The structure of Hilbert space imposes kinematic (i.e. pre-dymanic) objective probabilistic constraints on events to which a quantum dynamics of matter and fields is required to conform, through its symmetries [...]. [31]

And, as with relativity, they hold that there is no deeper explanation of the structure of events than that they are subject to the constraints embodied in the principles.

> There is no deeper explanation for the quantum phenomena of interference and entanglement than that provided by the structure of Hilbert space, just as there is no deeper explanation for the relativistic phenomena of Lorentz contraction and time dilation than that provided by the structure of Minkowski spacetime. [31]

In most cases these two ways of formulating a theory (principle and constructive) don't come into any kind of conflict. But in the case of the nonlinear extensions of quantum theory, the principle version of the theory makes different predictions than the constructive version. Following the dynamics of the systems under consideration leads us to conclude that signaling is effected in the BHW circuit. But this is in explicit conflict with the No-Signaling Principle.

### 3.5.2 Deutsch's Metaphysics

As I will argue in detail in Chapter 4, Deutsch's model requires a commitment to a deeper metaphysical picture than the principle–theoretic approach can support.

Deutsch frequently makes reference to the "multiverse" as the spacetime in which the events that solve the paradoxes of time travel occur. As an Everettian, he is committed to the existence of the branching structure that gives rise to the existence of many worlds. But there is additional structure needed to make the D-CTC model operate in the way he claims it does. The details of this will appear in the following chapter, but briefly, he is committed to the existence of the Many–Worlds Multiverse (MWM), and an additional structure I call the Mixed-State Multiverse (MSM).

The existence of the MSM is necessary for solutions of the following kind to obtain:

> In all universes the observer approaches the chronology-violating region on a trajectory which would go back in time. But only in half of them does the observer remain on that trajectory, because in half the universes there is an encounter with an older version of the observer after which the younger version changes course and does not go back in time. After that, both versions live on into the unambiguous future. [1]

It is the parallel worlds of the MSM that are connected by CTCs. This structure is not implicit in MWI itself, and is added by Deutsch as a solution to the paradoxes of time travel.

Since Deutsch's metaphysics plays such a central role in the formulation of his CTC model, it cannot be ignored. It is therefore problematic for quantum information theorists to adopt this model for analysis in a principle-theoretic context. Despite their claim to be neutral to questions of interpretation, the metaphysics is playing a fundamental role in the example.

As a consequence, the ease of fit is strained between principle–theoretic considerations that reify the No Signaling principle in a context where the fundamentality of underlying metaphysical considerations is denied, with a model that relies crucially on such commitments to yield the predicted behavior under consideration.

The D-CTC model requires a strong commitment to a particular ontology, and is therefore the product of a constructive version of quantum theory. On the constructive view, top–down principles are not considered to have any fundamental importance, and when they conflict with predictions based on the ontology and dynamics, they are discarded. The D-CTC model predicts signaling because of the commitments of the theoretical framework in which it was developed.

Can we embed the mathematical features of the D-CTC model in a principle–theoretic framework without making the same metaphysical commitments? As I argue in the following chapter, denying the D-CTC model recourse to the explanatory resources provided by realism about the ontology of MSM will lead it to make different predications in simple cases, undermining its ability to solve even the Grandfather Paradox.

The D-CTC model includes elements of both the metaphysical approaches to quantum theory, and quantum information. Although these two approaches come into conflict, I will argue that Deutsch had a consistent view in mind. His analysis of the power of quantum computation, for example, is based on parallelism. He considers the increased capabilities of a quantum computer to be proof of the existence of the parallel worlds in which the many computations necessarily must take place. Although this strong metaphysical commitment to the existence of parallel worlds is a minority view among contemporary QIT researchers, it is not strictly in conflict with it. It is in conflict, however, with the purely operationalist interpretation of quantum mechanics that leads to the principle–theoretic conception of fundamental physical theories.

### 3.5.3 Bub-Stairs Consistency

Another minor conflict with Deutsch's approach arises in the Bub and Stairs paper, and is related to the point about nonlocality and relativity from above. Bub and Stairs argue that their consistency condition allows for a "radio to the past", or a protocol for sending classical information back in time. They contend that the existence of this protocol opens the door to temporal paradox.

It has been argued convincingly in a number of places that the sending of superluminal signals is itself inconsistent with relativity. For example, Maudlin showed in [34] that there are hypersurfaces of superluminal signal reception that are Lorentz invariant. Furthermore, he argues that even in the case of a locus of reception that falls along the simultaneity surface defined by the state of motion of the emission source of the signal, there isn't a direct contradiction with relativistic constraints.

> On the other hand, Relativity *per se* in no way constraints case-1 signals. It is consistent even with case-1 superluminal signals which propagate instantaneously (i.e. along a flat space-like hyperplane). But the hyperplane must be in part determined by the state of the emitter, or of some other matter. [34]

What is problematic from a relativistic point of view is the fact that information can be sent to the past by chaining together superluminal signals, and in so doing, we apparently give rise to the possibility of contradictions (like the Grandfather Paradox).[2] For example, Timpson says

> The constraint is that superluminal signalling is ruled out on pain of temporal loop paradoxes. What this means is that no physical process is permissible that would allow a signal to be sent superluminally and thus allow information to be transmitted superluminally. [22]

This view is typical (see e.g. [34] and [30]).

This is what Bub and Stairs call a "radio to the past". As argued in Section 3.4.2, Deutsch's consistency condition wold apply to this classical information channel as well. Here it will suffice to say that the origin of the superluminal signaling in this debate is from the assumption that CTCs behave in such a way that

[2] The simple objection that superluminal signaling would violate relativity because the information is "traveling faster than light" can be answered by pointing out that there is nothing about exploiting quantum nonlocality to sent usable information that requires that a carrier of information physically traverses the space between the communicating parties. Quantum teleportation arguably involves sending quantum information (in the form of the unknown state $|\psi\rangle$) faster than light from Alice to Bob, though in order for Bob to use it, a two–bit classical message must be sent at subluminal speeds. See Timpson's discussion of teleportation in [22].

Deutsch's consistency condition holds. It is the consistency condition that induces the nonlinear evolution that leads to the ability to distinguish the BB84 states. However, there is the question of whether the D-CTC consistency condition should apply to information sent to the past in this way. Deutsch's model is motivated by the possible existence of CTCs as understood from a relativistic point of view. He mentions the consistency of wormholes with general relativity in the setup of his argument. But he also explicitly abstracts away from these spacetime structures in developing his model. He considers CTCs to be characterized by a closed path of information. If there is no closed path for information, then there is a denotationally trivial transformation that can eliminate all negative time delays. A spacetime that contains any effect of a closed loop of information is subject to his analysis.

> Negative delay components in the model play the role of time machines, which I define in general as objects in which some phenomenon characteristic only of chronology violation can reliably be observed. [...] The basic method of this paper is to regard computations as representative physical processes—representing the behavior of general physical systems under the unfamiliar circumstances of chronology violation. [1]

According to Deutsch, any physical system in which there is a closed loop of information can be represented as a CTC-supplemented computational circuit. Though he never explicitly addresses this issue, from what has been said, it seems clear that this should also apply to cases where the closed loop of information is made possible by the prior existence of a CTC, and the loop exists outside of what was originally taken to be the region of interaction.

The evidence for this claim is comes from the fact that Deutsch, as an Everettian, would deny that there was any principled distinction between classical information and quantum information. Ultimately, classical information supervenes on quantum systems. In order to be consistent with his broader view on the interpretation of quantum theory, he must treat the classical domain and the quantum domain as subject to the same laws, particularly one as fundamental as a consistency condition.

In fact, in his paper, he explicitly states that he is conceiving of computation for the purposes of this argument as

> a representative physical process—representing the behavior of general physical systems under the unfamiliar circumstances of chronology violation. [1]

He develops a standard form for a CTC-assisted quantum circuit for the purposes of defining his consistency condition in a simple way. But he says that any space-time bounded network, which he uses to represent general physical systems, can be trivially transformed into a denotationally equivalent standard form, which localize any closed loop of information onto a CTC.

> ...[T]he transformed version would be intuitively very different from the original one which might represent a time traveler, whereas the transformed version appears to represent an ordinary space traveler meeting a time traveler who spontaneously comes into existence as an identi-

> cal twin of the space traveler, exists for a finite period of time on an "eternal" loop, and then ceases to exist. [1]

It is clear that Deutsch takes these quantum-circuit representations to be completely general. Therefore, his consistency condition should apply to all physical systems.

Bub and Stairs consider the radio to the past protocol to be potentially paradoxical because they insist on a strict distinction between the classical domain and the quantum domain. They say that they see their consistency condition as allowing for a "radio to the past", which opens the door for the reemergence of the time travel paradoxes in the classical domain. This comes from the fact that they are implicitly taking on a Heisenberg (or operationalist) picture, which is characteristic of quantum information, but is rejected by the realist approaches to the interpretation of quantum theory. This is the same problem we saw above: the tenets of the quantum information-theoretic interpretation of quantum theory are doing work behind the scenes to justify the approach to the problem.

And finally, it should be noted that even in a purely classical context, there are analogues of Deutsch's consistency condition that are taken equally scientifically seriously (e.g. [19] and [20]). So even if they argue that Deutsch's consistency condition only applies to quantum information, there are consistency conditions in reserve ready to step in.

## 3.6 Conclusion

The considerable recent interest among the quantum information community in the D-CTC model has produced genuinely interesting results. The BHW circuit and its use in the Nonlocal Signaling protocol are considerable contributions to our understanding of how quantum systems behave in nonlinear extensions of quantum theory.

However, we must be sensitive to the fact that there are significant constraints on the generality of the D-CTC model. Its formulation presupposes significant metaphysical commitments, and is therefore applicable only in contexts where those metaphysical commitments are shared. Failing to recognize this feature of the model threatens to undermine its application. I argue that this problem is present in the debate in the quantum information literature, in particular in the attempts to impose the No-Signaling Principle on the framework in which the system is being analyzed.

Because of these underlying commitments, the D-CTC model serves as an important example for the divergence between the principle-theoretic approaches to quantum theory, and the more metaphysically robust constructive approaches. Deutsch himself is unambiguously an advocate of the latter, and the model is arguably incoherent on the former approach.

# Chapter 4: The Metaphysics of D-CTCs: On the Underlying Assumptions of Deutsch's Quantum Solution to the Paradoxes of Time Travel

## 4.1 Introduction

The possible existence of a closed timelike curve—a path in spacetime that takes a traveler to his own past—gives rise to the possibility of serious paradoxes. The paradoxes of time travel, which are well known to any fan of science fiction, demand a solution if we are to take seriously the possibility of the existence of CTCs. After all, the world can't admit of a physical situation in which the actions of a time traveler prevent the creation of his own time machine. The classical proposal for solutions to the time travel paradoxes simply states that such a situation could not obtain because it is inconsistent. That is to say, the classical solution is to impose a global property of self-consistency on the events in spacetime in order to rule out the possibility of paradoxical situations arising (see e.g. [19] and [20]).

David Deutsch argued in his 1991 paper "Quantum Mechanics Near Closed Timelike Lines" [1] that, under certain assumptions, quantum mechanics can solve the paradoxes associated with time travel to the past. What bothered Deutsch about the classical solutions to these paradoxes was the element of superdeterminism implicit in them. Certain initial states of systems are ruled out by these classical solutions, in order to preserve a global consistency. This is at odds with what Deutsch identifies as one of the fundamental principles of the philosophy of science: that global constraints should not overrule our ability to act locally in accord with the laws of physics. He calls this the *autonomy principle*. The classical consistency condition violates this principle by disallowing certain initial trajectories of systems traveling along CTCs.

Deutsch showed that taking quantum effects into account allowed for a solution to the paradoxes of time travel, without disallowing any initial states of the system. He showed that for any initial condition, there is a quantum fixed point solution representing a self-consistent physical state of the system. This is achieved by allowing for mixed quantum states to obtain on the CTC—a strategy to which solutions in the classical setting do not have access.

The Deutsch closed timelike curve (D-CTC) model has been influential in the quantum foundations literature as a plausible candidate for how negative time delays would work in terms of information flow (see e.g. [18], and more recently [46] and [41]). The operational features of the model are taken on board, and are considered to be unproblematic additions to the machinery of the quantum information approach.

Presumably, the justification in doing this comes from the assumption that the multiverse on which Deutsch is relying in his description of the D-CTC model is the "multiverse" of the Everett interpretation of quantum mechanics. If this were true, it could safely be ignored by those preferring an operationalist version of quantum theory, since the Everett interpretation is, after all, unmodified quantum theory.

However, Deutsch is relying on the existence of a more general notion of the multiverse, wherein the universes are not generated as the result of the Schrödinger evolution of the universal wavefunction, leading to the branching-off of macroscopic worlds, as in the standard Everett picture. Rather, the individual universes in this case exist timelessly and in parallel, many identical with one another for at least some period of time. These are not the many worlds of the Everett interpretation.

Part of the reason that this is confusing is that Deutsch refers to both of these objects by the term "multiverse". For my purposes, I will refer to the collective many worlds of the standard Everett interpretation as the *Many-Worlds Multiverse* (MWM). These are the result of branching of the universal wavefunction via decoherence. I'll refer to this other multiverse concept as the *Mixed-State Multiverse* (MSM). The reason for this will become clear. These universes are a kind of parallelism of existent worlds. They are not generated by the evolution of the quantum state of the universe. They timelessly exist in parallel with one another.

I will argue that a close analysis of the details of Deutsch's model shows that it cannot be so easily separated from his deep metaphysical commitments to the real existence of parallel universes. These parallel worlds are importantly different from the many worlds of the standard Everett interpretation, and as such, Deutsch's key structure is not supported by quantum theory.

Finally, I'll address the following question: Is it still possible to adopt the purely operational features of his model? I'll argue that Deutsch uses the existence of MSM in the reasoning about the operation of the model. I'll show, by considering a simple example, that a purely operational acceptance of the D-CTC model would allow for predictions that Deutsch explicitly rules out. That is to say, Deutsch relies on features of the implicit underlying metaphysical picture when defining the effects of his model, and without this influence, different predictions are possible.

## 4.2 Deutsch's CTC Model

As described in the Chapters 1 and 2, the D-CTC model was developed to solve the paradoxes of time travel in the case where the state of the system traveling into the past was described by quantum mechanics. The proposal has the feature of allowing for any initial state to be consistent with any interaction in the past, unlike the classical solutions to the paradoxes. Deutsch formulates his model in terms of the information flow of the physical situation.

Deutsch points out that chronology violation itself makes no difference to the behavior of a network unless there is a closed loop of information. In the original network, this closed information path could potentially not be confined to the trajectory of any single particle (since the carriers can interact with each other), but for any such network, there is a denotationally trivial transformation which will localize the closed information path on sufficiently many carriers on closed paths.

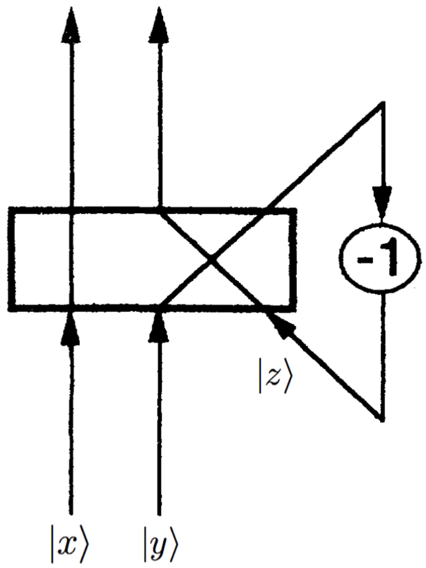
In the classical case, networks containing chronology violations can lead to paradoxes that seem to put unnaturally strong constraints on possible initial conditions of physical systems (e.g. you are somehow prohibited from getting in the time machine that would take you back to kill your grandfather). Deutsch uses his model to argue that, when quantum mechanics is taken into account, these unnatural constraints on initial states disappear. Deutsch's fixed point theorem states that CTCs "place no retrospective constraints on the state of a quantum system" [1]. That is to say, for any possible input state, there will be a paradox-free solution.

The puzzle arises, though, when we note that the CTC qubit must *always* have been in this state. There are no previous interactions with the CR qubit to force $\hat{\rho}$ to evolve over time into the state that guarantees consistency. Although Deutsch's model has avoided the superdeterminism of the classical solution to the time travel paradoxes, which constrained the initial states of the CR system, it seems to have introduced significant constraints in another place. Something like Lewis's classical consistency condition must still be at play. That is to say, there must be a deeper metaphysical justification (i.e. the impossibility of a self-contradictory history) which is behind Deutsch's quantum condition.

## 4.3 The Problem

Deutsch's example of a Grandfather Paradox circuit clearly shows how this effect works. He models the information flow in the way shown in Figure 1. The input states allowed in this setup are $|1\rangle_x |0\rangle_y$ and $|0\rangle_x |1\rangle_y$. The former represents an initial state with a time traveler present on a trajectory that *does not* take her through the CTC, and the latter represents an initial state with a time traveler on the trajectory that *does* take her through the CTC. That is, when $x = 1$ and $y = 0$,

Figure 4.1: The grandfather paradox circuit. From [1].




no time travel occurs. But when $x = 0$ and $y = 1$, a grandfather paradox becomes a possibility.

There are three inputs to the rectangular region of interaction, $|x\rangle$, $|y\rangle$, and the older version of the second qubit after it has traversed the CTC, which will be referred to as $|z\rangle$. Since $|z\rangle$ is simply an older version of $|y\rangle$ after they interact, and by stipulation there is no evolution of the state of the qubit on the CTC, the post-interaction state of $|y\rangle$ must equal the pre-interaction state of $|z\rangle$. This is a statement of Deutsch's consistency condition.

In the classical version of this circuit, the particles must be in pure states. The state of $|z\rangle$ is equal to $x \oplus 1$, because all that is being represented in this model is the presence of a bit on that channel. If $x = 1$, then no bit will go around the CTC. If $x = 0$, then there is a bit present on the CTC.

To enact the grandfather paradox, Deutsch sets the interaction in the region to be:

$$|x\rangle_x |y\rangle_y |x \oplus 1\rangle_z \Rightarrow |x \oplus x \oplus 1\rangle_x |y \oplus x \oplus 1\rangle_y |x \oplus 1\rangle_z .$$

As noted above, the post-interaction state of $|y\rangle$ must be equal to the pre-interaction state of $|z\rangle$. That is, the following equivalence must hold:

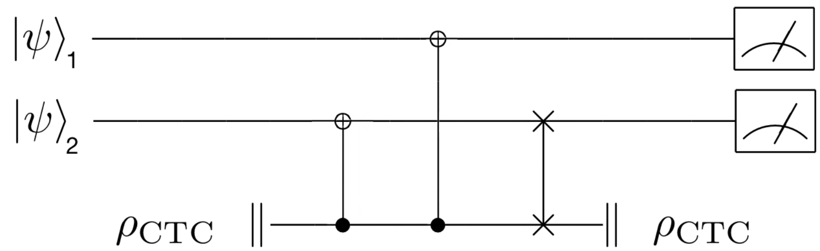
$$y \oplus x \oplus 1 = x \oplus 1.$$

In the classical case, this can only be true if $x = 1$ and $y = 0$, meaning that no time traveler ever went back to prevent herself from traveling. The input state $x = 0$ and $y = 1$ would not yield a consistent solution, and is therefore ruled out. That would represent a situation where the time traveler succeeded in going back in time and prevented herself from entering the future mouth of the CTC. This paradoxical situation can not obtain, so the classical consistency condition rules out this input state.

The quantum solution must be formulated in terms of the fully transformed circuit—something Deutsch refrains from doing explicitly in [1]. However, when the quantum solution is clearly diagrammed, the seeds of the problem for Detusch's account becomes apparent. The first two interactions from the CR perspective are "controlled–NOT" gates. That means that if the controlling qubit (in this case, $\rho_{\mathrm{CTC}}$) is in the state $|1\rangle$, then it will effect a NOT transformation on the target system.[1] The third interaction is SWAP, where the state of the system $|\psi\rangle_2$ is

[1]NOT is the "bitflip" operation, which takes $|0\rangle \rightarrow |1\rangle$ and $|1\rangle \rightarrow |0\rangle$. This is equivalent to the interaction from Deutsch's example, where the value of bit $z$ is added to $x$ and to $y$.

Figure 4.2: The fully-transformed grandfather paradox circuit. Two CNOT interactions, followed by a SWAP.




exchanged for the state of $\rho_{\text{CTC}}$. The information flow here is identical to the partially-transformed circuit of Deutsch's example. However, whereas the state of the bit $|z\rangle$ from the first circuit is clearly dependent on the state of $|x\rangle$ (e.g. if $x = 1$, then $y = 0$, and there would be no bit to travel around the CTC), in the fully-transformed version the state of $\rho_{\text{CTC}}$ is clearly *uncaused*. The independence of the state of the system confined to the CTC is more obvious in this version of the circuit.

It is this feature of the fully-transformed circuit that Deutsch relies on for the quantum solution to the paradox. From the CR perspective, $\rho_{\text{CTC}}$ has always been in the particular mixed state that allows for the success of the circut. When $\rho_{\text{CTC}} = \frac{1}{2}\hat{I}$, then there will be a self-consistent solution for the classically forbidden input state $|0\rangle_1 |1\rangle_2$. This will yield the following output:

$$\hat{\rho} = \frac{1}{2} \left( |00\rangle \langle 00| + |11\rangle \langle 11| \right).$$

This mixed output state is interpreted by Deutsch as indicating that there are many separate worlds in which the two possible outcomes happen. The solution relies on the existence of parallel worlds into which a time traveling system goes when passing though a CTC.

> The key thing to bear in mind when trying to visualize it is that in half of the universes (let us call them the "$A$ universes") the encounter happens and in the other half (the "$B$ universes") it does not happen. [...] In the $A$ universes an observer appears "from nowhere" (no one having embarked on a chronology-violating trajectory in that universe) and in the $B$ universes an observer enters and disappears "into nowhere" (since no one has emerged on the chronology-violating trajectory in that universe). But of course it is not really "from nowhere" and "into nowhere," but from and into other universes. [1]

For Deutsch, the mixed state $\frac{1}{2}\hat{I}$ represents the connection between parallel worlds. In half of them the state of the system on the CTC is $|0\rangle$, and in the other half the state is $|1\rangle$. They travel across these bridges, into parallel worlds and interact with the CR systems there. The overall ensemble of states in these separate universes is the object to which the consistency condition applies.

> In the Everett interpretation it is only the state, which describes, roughly speaking, a collection of values taken as a whole, which must be unchanged after passage round a closed timelike line. [1]

The mixed state representing the collection of worlds must be self-consistent, but as we saw from the above example, the actual outputs of the circuit will be different in different universes, meaning in some the state that the CR qubits interact with is $|0\rangle$, and in the others it is $|1\rangle$.

## 4.4 MWM vs. MSM

Deutsch's model is often adopted wholesale by theorists working in the foundations of quantum theory. Deutsch's talk of travel between parallel worlds is thought to be unproblematic because it is assumed that he is simply adopting the language of the Everett interpretation of quantum theory.

But there is an immediate problem with this interpretation of Deutsch's model. Imagine a time traveler traveling from $t = 2$ back in time to $t = 1$. She can't be traveling into her own past, because her presence there would change it, leading to a different future evolution of the wavefunction, undermining the existence of the branch from which she came. She needs to travel to an already existent branch with an identical copy of herself at $t = 1$. The problem is, according to the Everett interpretation, there would be no such branch. Since the state of the world at $t = 1$ in the time traveler's actual past is, by stipulation, identical to the state of the world at $t = 1$ in the universe into which she is traveling, there would never have been a branching event that would have created multiple copies of the world.[2] The existence of this destination world is not consistent with the branching structure of the standard Everett interpretation. Deutsch cannot be relying on the structure of MWM for his solution to the paradoxes of time travel.

[2]This would, of course, be a multiplicity of branches on which the state of the world is slightly different from the state in the time traveler's past, but Deutsch requires that time travel be between worlds with *identical* histories.

However, this logical problem is obscured by the fact that Deutsch often talks about the Everett interpretation in terms of parallel existent worlds (e.g. see [11]). Deutsch admits that this talk of parallelism represents nothing more than a convenient approximation to the Everett interpretation, to be used with care. He states this explicitly and often:

> The idea that quantum theory is a true description of physical reality led Everett and many subsequent investigators to explain quantum-mechanical phenomena in terms of the simultaneous existence of parallel universes or histories. [...] However, if reality—which in this context is called the *multiverse*—is indeed literally quantum-mechanical, then it must have a great deal more structure than merely a collection of entities each resembling the universe of classical physics. For one thing, elements of such a collection would indeed be 'parallel': they would have no effect on each other, and would therefore not exhibit quantum interference. For another, a 'universe' is a global construct—say, the whole of space and its contents at a given time—*but since quantum interactions are local, it must in the first instance be local physical systems, such as qubits, measuring instruments and observers, that are split into multiple copies, and this multiplicity must propagate across the multiverse at subluminal speeds.* [10, emphasis added]

If the D-CTC model cannot be embedded in the standard branching MWM, how then is it supposed to work? I will argue that a close reading of Deutsch reveals that he has a very particular metaphysical view: He is a realist about the existence of many (possibly infinitely many) parallel worlds, which differ from MWM. That is to say, in addition to the many worlds that exist in the Everett interpretation as the result of the evolution of the wavefunction, he also is committed to the existence of a multiverse whose worlds exist eternally, and any two of which may be identical to one another for some or all of their histories.

I argue that the D-CTC model is crucially grounded in his commitment to this metaphysical view. The density matrices that represent the mixtures on the CTC are, for Deutsch, a collection of parallel worlds. But these worlds could not exist as the result of branching of the wavefunction. Part of the difficulty in developing a clear picture of his commitments comes from the fact that Deutsch has presented his solutions to the paradoxes of time travel in popular works much more frequently than in scholarly works. But I will suggest that a clear picture of what he has in mind can still be developed.

It's clear from his popular discussions of his D-CTC model that he considers a kind of parallelism to be conceptually foundational to his solutions to the paradoxes of time travel (see [43] and [11, Ch. 12]). The grandfather paradox is solved (while preserving the autonomy principle), because time travel takes us into a another universe. A time traveler is free to kill the person she meets there (a counterpart of her own grandfather), because she will not actually be altering her own past. Rather, she is participating in the past of another universe.

In these writings, he claims to ground the existence of these parallel worlds in the Everett interpretation.

> According to Everett, if something physically can happen, it does—in some universe. Physical reality consists of a collection of universes, sometimes called a multiverse. [...] What then, does quantum mechanics, by Everett's interpretation, say about time travel paradoxes? Well, the grandfather paradox, for one, does not arise. [...] If the classical space-time contains CTCs, then, according to quantum mechanics, the universes in the multiverse must be linked up in an unusual way. Instead of having many disjoint, parallel universes, each containing CTCs, we have in effect a single, convoluted space-time consisting of many connected universes. [43]

However, for the reasons discussed above, the universes he describes cannot be the result of branching. Universes only branch off from one another when there are significant enough differences between them such that they would lead to macroscopically distinguishable worlds. As he says in [47], Everett worlds are emergent, and result from the process of decoherence.

> ...Only [the Everett interpretation] can accommodate the fact that universes turn out to be approximate, emergent structures in the multiverse.[3] Decoherence theory opened up the study of the structure of the multiverse: not just how the quasiclassical universes emerge, but also how what is happening exactly when the universes are present emer-

[3]When discussing the Everett interpretation, Deutsch's terminology varies from the standard. As he says in [48] "I'm quite happy to call the multiverse the universe and the universe a branch." This sentence should be understood to mean that branches emerge via decoherence, and are elements of the universal wavefunction. This is consistent with Wallace's presentation in [49].

gently. [47]

But compare that to the statement of the existence of the parallel worlds he makes in [43]:

> If the classical space-time contains CTCs, then, according to quantum mechanics, the universes in the multiverse must be linked up in an unusual way. Instead of having many disjoint, parallel universes, each containing CTCs, we have in effect a single, convoluted space-time consisting of many connected universes. The links force [the time traveler] to travel to a universe that is identical, up to the instant of her arrival, with the one she left, but that is thereafter different because of her presence. [43]

Deutsch considers it a lesson of this analysis that there are multiple parallel worlds connected up in the right kind of way.

> So, for time travel to be physically possible it is necessary for there to be a multiverse. And it is necessary that the physical laws governing the multiverse be such that, in the presence of a time machine and potential time travellers, the universes become interconnected in the way I have described, and not in any other way. [11]

But these are not the many worlds of the branching Everett model. They are from some larger multiverse.

What is needed is to express such arguments in the framework of a

> theory of a multiverse—sometimes it has to be a bigger multiverse than Everett's. [47]

What grounds this talk of parallelism? The root of the idea has to do with the fact that the state $\rho_{\text{CTC}}$ is mixed in the solution to the paradox. This mixed state does not arise as the result of the evolution of the system from its initial conditions. Rather, it is induced by the presence of the CTC.

## 4.5 Mixed States Bound to the CTC

The power of the D-CTC model is that it allows for the information flow bound to the CTC to be in a mixed state, which can solve the classically paradoxical situations. For example, in the Grandfather Paradox circuit, it is because the closed loop of information bound to the CTC is free to be in the state $\frac{1}{2}\hat{I}$ when the input state is $|0\rangle_1 |1\rangle_2$ that there is a self-consistent solution.

But where do these mixed state come from? It might be argued that the reason the state exiting the past mouth of the CTC in Figure 2 is $\frac{1}{2}\hat{I}$ is because the interaction that $|\psi\rangle_2$ underwent *caused* it to be so. But this reasoning implicitly relies on a pseudotime narrative of the interaction. Deutsch explicitly denies that the mixed state should be interpreted as a statistical ensemble. And in reality, there is no beginning to the existence of the state bound to the CTC. It is a closed loop of information, and as such can have no external cause. It must therefore be a feature of the existence of the CTCs that allow those systems to evolve from pure states into mixed states.

These states simply exist, present on the CTC, not caused by any interaction, and therefore not explainable. This is another way of stating the additional element of superdeterminism present in his model—it is this structure that he takes to ground his claim that the universes simply "connect up" in the right way.

Since the state on the CTC isn't caused by the interaction with the initial state, but merely exists because it allows for a consistent solution, this gives rise to the existence of an alternative prediction. Deutsch gives an extra-theoretic answer to why the following solution is ruled out. For now, we will simply note that it is in accord with the requirements of the consistency condition.

When describing the classical version of the Grandfather Paradox circuit (Figure 1), Deutsch defines the state of the bit $|z\rangle$ as $|x \oplus 1\rangle$. That is to say, if we start with the time traveler present on the trajectory that avoids the CTC (represented by $x = 1$, $y = 0$), then there won't be anything to travel around it, and if the time traveler starts on the trajectory that will take her through the CTC (represented by $x = 0$, $y = 1$), then the CTC will be occupied. So the state on the CTC should be the opposite of $|x\rangle$.

But in this fully transformed version of the circuit, the independence of the state of the system on the CTC (representing the closed loop of information) is more obvious. The only condition is that the state of $\rho_{\text{CTC}}$ when it enters the future mouth of the CTC is the same as the state of $\rho_{\text{CTC}}$ as it exits the past mouth of the CTC.

Since there is no way to account for why $\rho_{\text{CTC}}$ takes on the particular value it does when exiting the past mouth of the CTC in the cases where it solves the paradox—after all, it is uncaused—then there is likewise no way to account for why $\rho_{\text{CTC}}$ has the state it does when exiting the past mouth of the CTC when its state is irrelevant to a paradox. The only condition in the former case is that its state is consistent with $\rho_{\text{CTC}}$ entering the future mouth. It seems that this should be the same in the latter case.

If that's true, then there is another consistent solution to the case where the initial state of the system is $|1\rangle_x |0\rangle_y$, namely the one that takes the final state to $|0\rangle_x |1\rangle_y$. If the system $\rho_{\text{CTC}}$ exits the past mouth of the CTC in the state $|1\rangle_z$, then the effect of the two CNOT gates will evolve the system in the following way $|1\rangle_x |0\rangle_y \Rightarrow |0\rangle_x |1\rangle_y$, and then the SWAP gate will have no effect.

In the notation of the example from [1], we are denying that the state of $|z\rangle$ should equal $|x \oplus 1\rangle$. Since $|z\rangle$ can take on any state, there are two solutions to the input state $|1\rangle_x |0\rangle_y$. Recall, the interaction was defined as:

$$|x\rangle_x |y\rangle_y |x \oplus 1\rangle_z \Rightarrow |x \oplus x \oplus 1\rangle_x |y \oplus x \oplus 1\rangle_y |x \oplus 1\rangle_z$$

which, with the modification under consideration becomes:

$$|x\rangle_x |y\rangle_y |z\rangle_z \Rightarrow |x \oplus z\rangle_x |y \oplus z\rangle_y |z\rangle_z$$

The consistency condition requires that the pre-interaction state of $|z\rangle$ equals the post-interaction state of $|y\rangle$.

The standard solution for the input $|1\rangle_x |0\rangle_y$, where $z = 0$ still obviously holds.

But there is also a consistent solution for when $z = 1$:

$$|1\rangle_x |0\rangle_y |1\rangle_z \Rightarrow |1 \oplus 1\rangle_x |0 \oplus 1\rangle_y |1\rangle_z = |0\rangle_x |1\rangle_y |1\rangle_z$$

Deutsch would argue that this is an unphysical solution. Since the CTC is not in use, in all the identical parallel universes (to which a CTC could potentially connect us), the CTC will also be unused.

> For example, if I am not going to use a time machine come what may, then no time-travelling versions of me must appear in my snapshot[4]; that is, no universes in which versions of me do use a time machine can become connected to my universe. If I am definitely going to use the time machine, then my universe must become connected to another universe in which I also definitely use it. And if I am going to try to enact a 'paradox' then, as we have seen, my universe must become connected with another one in which a copy of me has the same intention as I do, but by carrying out that intention ends up behaving differently from me. [11]

Therefore, the qubit that exists the CTC couldn't have come from anywhere. Deutsch says that the way the universes connect up depends on the intentions of the time traveler.

A real time machine, of course, would not face these problems. It would

[4]He is using the term "snapshot" as an analogue for "timeslice" in this more general multiverse framework where a unique time ordering of a foliation may not be possible.

> simply provide pathways along which I and my counterparts, who already existed, could meet, and it would constrain neither our behaviour nor our interactions when we did meet. The ways in which the pathways interconnect—that is, which snapshots the time machine would lead to—would be affected by my physical state, including my state of mind. That is no different from the usual situation, in which my physical state, as reflected in my propensity to behave in various ways, affects what happens. [11]

But this explanation requires the acceptance of the existence of the parallel universes of MSM. To attempt to adopt Deutsch's model without also bringing this sizable metaphysical commitment on board would leave you no way to rule out our alternative prediction.

## 4.6 Comments

To accept the D-CTC model, it seems necessary to accept that the state of the universe is a density matrix with each elements corresponding to a physically real parallel world, which can, in the presence of a CTC, get connected up with our world, so that a collection of these separate universes all contribute elements to the ensemble of states that is present on the CTC, ensuring that interactions with the CR system will leave the ensemble in same state in which it began.

Deutsch includes a discussion of this possibility in a rather oblique way in [1]. He argues that, since the existence of a CTC allows for a pure state to evolve into a mixed state, it may be worth reconsidering the question of whether it is possible that the whole universe should be described by a density matrix $\hat{\rho}(t)$:

> $\hat{\rho}(t)$ therefore describes a collection of "universes" (each one itself consisting of multiple universes under the Everett interpretation), one for each nonzero $p_i$. Each evolves precisely as if the others were absent and it had a pure state $|\psi_i(t)\rangle$. This is quite unlike the Everett multivaluedness caused by the linear superposition of components of a state vector, which is detectable through interference phenomena. Thus the cosmology described by $\hat{\rho}(t)$ contains a multiplicity of mutually disconnected and unobservable entities and is vulnerable to the "Occam's razor" argument that is sometimes erroneously leveled against the Everett interpretation.
>
> But in the presence of closed timelike lines the evolution with respect to an external time coordinate is not longer necessarily unitary as in (38). [...] Therefore in principle it might be possible to detect experimentally the difference between distinct density operators with identical eigenstates, so the "Occam's razor" argument no longer necessarily holds. [1]

Of course, the existence of the mixed state on the CTC, which is required by Deutsch's consistency condition, is the *reason* a pure state will evolve into a mixed state. And the interpretation of those mixed states presupposes that the universe is itself in a mixed state. Deutsch is using the claim that D-CTCs are supported by the Everett interpretation to bolster their credibility, and using their predictions to argue for the existence of MSM. But D-CTCs are only supported by Everett if you already accept that MSM is consistent with the Everett interpretation, and that the Everett worlds don't need to be the result of the Schrödinger evolution of the wavefunction and decoherence.

The majority of people writing on D-CTCs are interested in questions about quantum information and quantum computation, and generally think of the debates over the interpretation of quantum theory to be superfluous. To what degree could the operational feature of the D-CTC model be accepted without any commitment to the underlying metaphysics?

The example of the alternative solution to the Grandfather Paradox circuit from the last section undermines the idea that D-CTCs can be operationally adopted without consequence. Deutsch would rule out the prediction, but his justification for this relies on his interpretation of the model, and not simply on the consistency condition. He would argue that the solution is impossible because the universes aren't connected up in the right way, because the state on CTC is sensitive to the intentions of nearby experimentalists. This kind of explanation would not be formulable without reference to the existence of the parallel worlds. And without recourse to this explanation, it seems as though an operationalists who wish to adopt the D-CTC model will need to accept that it makes predictions different from Deutsch's in simple cases. That is to say, his solutions to the paradoxes of time travel—which motivated the adoption of this model in the first place—fail.

This analysis is by no means meant to undermine Deutsch's model—if you accept his assumptions, there is no problem. However, it is meant to challenge the claim that there is a quantum mechanical solution to the Grandfather Paradox. It is often claimed that the resources of the Everett interpretation (the existence of the Everett worlds) allow for a solution to the paradox. This is not so. Deutsch's solutions to the paradoxes of time travel are ingenious and fascinating, but they proceed from a substantive metaphysical commitment that takes them beyond the domain of pure quantum theory.

# Chapter 5: Shakespeare's Free Lunch: A Critique of the D-CTC Solution to the Knowledge Paradox

## 5.1 Introduction

In this paper I will develop an example that casts doubt on the strength of Deutsch's solution to the Knowledge Paradox. I will argue that because of the metaphysical commitments that underwrite Deutsch's CTC model, he is committed to the existence of worlds that undermine his proposed solution to the paradox. I will suggest that there is a distinction available to Deutsch on which he can rely to alleviate some of this tension, but it too comes at a cost. The invocation of this distinction would have served as a solution to the existence of Knowledge Paradox worlds prior to Deutsch having to develop a solution based on the D-CTC model. This calls into question the claim he makes that the features unique to the D-CTC model offer the best solutions to the paradoxes of time travel.

I will begin by discussing some general features of the concept of the *consistency condition* solution to the paradoxes of time travel. The two paradoxes on which I will be focusing my attention are the *Grandfather Paradox*, in which the effect of a time traveling system's presence in the past is to prevent that system from time traveling, and the *Knowledge Paradox*, in which a time traveling system leaves some information trace in the past which is ultimately causally responsible for its time travel.[1]

Most analyses of time travel attempt to rule out the possibilities of both of these effects. The inability to rule them out is often seen as a major flaw of a proposed analysis. I will argue, however, that although the *Grandfather Paradox* is a genuine paradox—that is, it contains a contradiction—the *Knowledge Paradox* is not, and its possibility should not be seen as a fatal flaw for an account of the possibility of time travel.

I introduce the well-known *Classical Consistency Condition* (CCC) solution to the Grandfather Paradox. The principle's first appearance in the philosophical literature was in a paper by David Lewis from 1976 [19], based on a series of lectures he gave in 1971. However, Lewis is clear in his paper that he drew his inspiration from science fiction, and he believed that the consistency condition was well-known to savvy science fiction authors and fans alike.

I will go on to consider a more recent debate about the nature of consistency in the presence of CTCs, which takes place in the context of the debate between proponents of D-CTCs, and the proponents of the alternative P-CTC model, which will be introduced below. I will argue that an analysis of Lewis's CCC will illuminate a sense in which the consistency condition in the D-CTC model is playing a very different role from the consistency condition in the P-CTC model, which is much

[1] This paradox is also variously called the *Information Paradox*, the *Unproved Theorem* paradox, the *Works of Shakespeare* paradox, and the *Uncaused Effect* paradox.

closer to Lewis's classical version.

In light of this difference, I will argue that the consistency condition in the D-CTC model only solves the two paradoxes in conjunction with Deutsch's metaphysical commitment to the reality of the MWM and MSM worlds. This commitment carries with it new problems for an analysis of time travel. I will examine one of these problematic features of time travel in MWI in detail, and I will argue that it undermines Deutsch's solution to the Knowledge Paradox from the D-CTC model.

Even though his model may have the resources to solve these problems to his satisfaction, it comes at a rather high cost. I'll also argue that the justification Deutsch uses for ruling out Information Paradox scenarios (he makes reference to "philosophical principles") isn't as strong as he claims. I'll give an example of another equally convincing philosophical position according to which these kinds of scenarios are possible. I'll conclude by arguing that ruling out the Information Paradox isn't a necessary part of a successful model of CTCs, and the fact that the P-CTC model doesn't rule them out shouldn't count as a strike against it.

## 5.2 The Consistency Condition in the Philosophy Literature

David Lewis's 1976 paper "The Paradoxes of Time Travel" was the first serious philosophical analysis of the logical paradoxes seemingly inherent in time travel. Lewis argued that time travel was in fact logically possible, and that the possibility that time travel seems to entail the existence of Grandfather Paradox scenarios was not enough to show that time travel narratives were inconsistent.

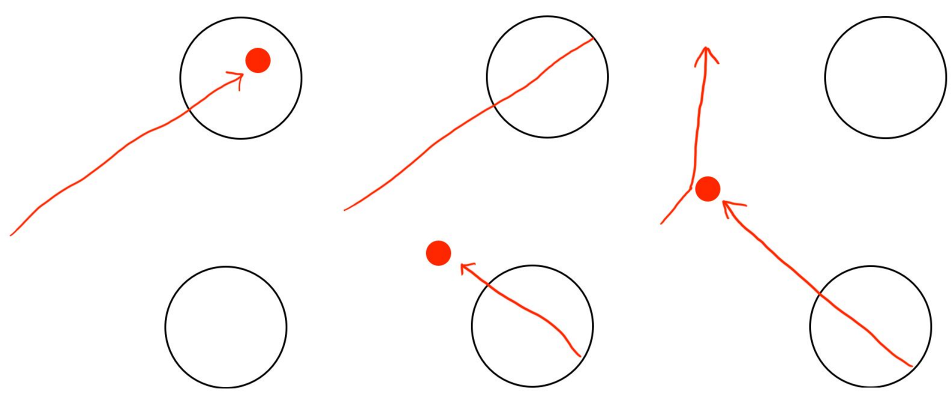
He introduced the CCC, which states that scenarios in which a time traveler kills his own grandfather cannot occur because they contain a contradiction. There are not two different versions of the past—one in which the time traveler wasn't present, and his grandfather lived, and one in which the time traveler was present and his grandfather was killed. Rather, there is just a single "run" of time, and it must be self-consistent.

> Either the events of 1921 timelessly do include Tim's killing of Grandfather, or else they timelessly don't. We may be tempted to speak of the 'original' 1921 which lies in Tim's personal past, many years before his birth, in which Grandfather lived; and of the 'new' 1921 in which Tim now finds himself waiting in ambush to kill Grandfather. But if we do speak so, we merely confer two names on one thing. The events of 1921 are doubly located in Tim's (extended) personal time, like the trestle on the railway, but the 'original' 1921 and the 'new' 1921 are one and the same. If Tim did not kill Grandfather in the 'original' 1921, then if he does kill Grandfather in the 'new' 1921, he must both kill and not kill Grandfather in 1921—in the one and only 1921, which is both the 'new' and 'original' 1921. [19]

Lewis's version of the consistency condition is the requirement that the single history in which all events take place be self-consistent. This self-consistency rules out all histories in which a time traveler somehow prevents himself from time traveling, since those histories would contain a contradiction.

This is identical to what physicists call the "Novikov Principle", though Lewis's statement of the principle predated Novikov's in print. Novikov's version of the CCC is formulated purely in terms of the behavior of simple physical systems. He begins by noting that, for every CTC, there is a trajectory along which one could send a billiard ball, such that the older version of the ball exiting the past mouth of the wormhole would interfere with the trajectory of the younger version heading towards the future mouth. Setting the ball along this initial trajectory enacts a Grandfather Paradox, since the ball is preventing itself from time traveling.

Figure 5.1: A billiard ball on a Grandfather Paradox trajectory. First the younger version enters the future mouth of the wormhole. Then the older version exits the past mouth of the wormhole. Then the older version interferes with the original trajectory of the younger version, preventing it from entering the future mouth.



Most of the trajectories that involve self–interaction are unproblematic—a slight nudge in one direction or the other from the older version ensures that the younger version is on a slightly altered trajectory, so that when it exits the past mouth of the wormhole as the older version, it only just nudges its younger counterpart. These are the consistent solutions to the problem of self–interaction.

However, certain initial trajectories do entail a Grandfather Paradox interaction. These initial conditions are ruled out by Novikov's consistency principle. Like Lewis, Novikov requires that the history of events be self-consistent. Therefore, certain initial states cannot obtain. In this sense, the two version of CCC both impose superdeterminism.

Deutsch believes that this constraint violates a "fundamental principle that underwrites both science and everyday reasoning" called the *autonomy principle*. He characterizes the principle in the following way

> According to this principle, it is possible to create in our immediate environment any configuration of matter the laws of physics permit locally, without reference to what the rest of the universe may be doing. [43]

CCC violates this principle, however, because it rules out the possibility of certain experimental setups, namely those which would send the billiard ball on a Grandfather Paradox trajectory.

> [CCC] states that the only configurations of matter that can occur locally are those that are self–consistent globally. Under this principle, the world outside the laboratory can physically constrain our actions inside, even if everything we do is consistent, locally, with the laws of physics. Ordinarily we are unaware of this constraint, because the autonomy and consistency principles never come into conflict. But classically, in the presence of CTCs, they do.

The characteristic feature of both of these formulations of CCC is that they rely only on a single history of the world to solve the Grandfather Paradox. They require simply that the single history of the universe contain no contradictions—that it be self-consistent. It is this feature that is shared by the P-CTC consistency condition, and which differs in the D-CTC model.

## 5.3 P-CTC Consistency v. D-CTC Consistency

The versions of the consistency condition which appear in the P-CTC model and the D-CTC model are formulated rather differently than Lewis's CCC. And although the two quantum consistency conditions appear to be very similar, I will argue that the P-CTC consistency condition is in fact closer in an important way to CCC, and that the D-CTC consistency condition is very different.

The main alternative approach to giving a quantum mechanical analysis of CTCs is the P-CTC approach, where "P" stands "post-selected". The approach begins by conceiving of the CTC as a quantum communication channel to the past. For this reason, the quantum teleportation protocol is taken as the starting place for the P-CTC model. Seth Lloyd, one of the prominent proponents of this approach says

> [...] If quantum teleportation is combined with post-selection, then the result is a quantum channel to the past. The entanglement occurs between the forward- and backward- going parts of the curve, and post-selection replaces the quantum measurement and obviates the need for classical communication, allowing time travel to take place. [16]

Consistency in the P-CTC model is achieved via post-selection. In the conventional teleportation protocol, in order for Alice to teleport the (potentially unknown) state $|\psi\rangle$ to Bob, they must first share a pair of maximally entangled particles. Alice makes a joint measurement on $|\psi\rangle$ and her half of the entangled pair. Based on the outcome she gets, she will communicate to Bob (via a classical channel) which one of four operations he could perform on his half of the entangled pair to produce $|\psi\rangle$ for himself. One of the four operations Alice might instruct Bob to undertake is to *do nothing* to his particle. That is to say, in 25% of the cases, Bob will already have a particle in the state $|\psi\rangle$ before he receives Alice's communication.

If we select out just these cases, then we can conceive of this as a situation where the state $|\psi\rangle$ is instantaneously teleported to Bob. In an experimental setting, by limiting our attention to the subset of results that have this feature, a P-CTC can be effectively simulated. It's important to note that, since the teleportation protocol preserves entanglement, the P-CTC model has the same feature. The state $|\psi\rangle$ may be entangled with other systems, and a P-CTC would displace this entanglement into the past.

One of the major differences between the D-CTC model and the P-CTC model is the form the consistency condition takes. The P-CTC consistency condition, as described by Lloyd as follows:

> [...] A generalized measurement made on the state entering the curve should yield the same results, including correlations with other measurements, as would occur if the same measurement were made on the state emerging from the curve. The CTC should behave like an ideal quantum

channel [...]. [17]

What's required to be consistent in this framework is a measurement on the state of the system at the future mouth of the CTC must be the same as a measurement on the state that emerges from the past mouth. This entails that the single history of the world in which all events take place be self-consistent. In this respect it is similar to the CCC.

D-CTC consistency does not share this feature. Recall Deutsch's mathematical statement of the consistency condition:

$$\rho_{\mathrm{CTC}} = \mathrm{Tr}_{\mathrm{sys}} \left[ V \left( |\psi\rangle \langle\psi| \otimes \rho_{\mathrm{CTC}} \right) V^{\dagger} \right]$$

It is only the state of the system bound to the CTC that must be the same at both mouths. This does not guarantee that the correlations with other systems that would have obtained had we measured the CTC-bound system prior to its entering the future mouth of the CTC be preserved when it exists that past mouth.

As I argued in Chapter 4, Deutsch's interpretation of the mixed state is crucial for the model to make the predictions he needs. The relevant features of that interpretation are that the mixed state that enters the CTC represents a collection of distinct worlds, in half of which the quibit is in state $|0\rangle$, and in half of which the qubit is in state $|1\rangle$, and that the CTCs are "'gateways' between Everett universes" [1]. As I argued in Chapter 4, there is a distinction to be drawn between the way in which the D-CTC model relies on the many worlds of the Everett interpretation (MWM), and the parallel existent worlds Deutsch introduces (MSM). His solutions to the paradoxes of time travel rely on the existence of the MSM worlds, but he is equally committed to the existence of both kinds of multiverse objects.

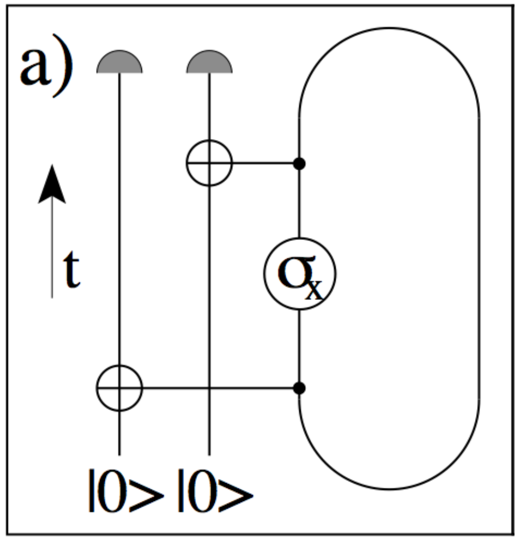
In the D-CTC model, $\rho_{\mathrm{CTC}}$ represents a collection of worlds, which are connected with each other via the CTCs. Deutsch's consistency condition applies to *this* object. The collection of worlds picked out by $\rho_{\mathrm{CTC}}$ is required to be self-consistent overall, but each individual world may undergo changes.

The main difference between the P-CTC and D-CTC consistency conditions is that the state of the system exiting the past mouth of a P-CTC must give rise to the same measurement outcomes as the state that entered the future mouth. Notably, this includes correlations of outcomes between the system on the CTC and CR systems. If the system traveling around the CTC is entangled with one of the CR qubits, that entanglement would be preserved when the system is sent to the past. Lloyd et al. impose this condition because they interpret it as being more true to the CCC. As Lloyd et al. say, "our mechanism embodies in a natural way the Novikov principle that only logically self-consistent sequences of events occur in the universe" [17]. Deutsch's consistency condition does not have this feature. The D-CTC model breaks entanglement between the CTC-bound qubit and any system in the CR region.

Lloyd uses the following Grandfather Paradox circuit to distinguish between the two approaches.

The system bound to the CTC is only stable in the state $\rho = \frac{1}{2}\left(|0\rangle\langle 0| + |1\rangle\langle 1|\right)$, because each "time" it goes around the CTC (in pseudotime) its state is flipped from $|1\rangle$ to $|0\rangle$, or from $|0\rangle$ to $|1\rangle$.

Figure 5.2: The Grandfather Paradox circuit from [17]




Deutsch interprets this as representative of real physical systems in the definite states $|1\rangle$ and $|0\rangle$, that, when taken together, constitute the mixed state on the CTC. As Lloyd says

> The strange aspect of Deutsch's solution comes when one attempts to follow the state of the time-traveller through the CTC. To preserve self-consistency, the 1 component (time traveller alive) that enters the loop emerges as the 0 component (time traveller dead), while the 0 component (time traveller dead) that enters the loop emerges as the 1 component (time traveller alive). Thus, the CTC preserves the overall mixed state, but not the identity of the components [...]. [17]

This aspect of the D-CTC model is explained by the fact that Deutsch conceives of these time travel scenarios as playing out in the parallel worlds of the MSM. On Deutsch's model, what is required to be consistent is the make-up of the collection of worlds which realize the mixed state on the CTC. For each individual world, however, there is no need for a prohibition against killing grandfathers. There will be worlds in which time travelers appear and kill people who look and act very much like their own grandfathers, but this is not inconsistent because in addition to being time travelers, these murderous adventurers are also *MSM world* travelers. They came from a world in which their own grandfather was alive, and traveled to a different world in which they kill a *counterpart* of their own grandfather. Each time traveler can kill the grandfather they find, because he isn't actually their own, and killing someone else's grandfather does not create a paradox.

On the P-CTC model, however, a different outcome is predicted.

> In any real-world situations, the $\sigma_x$ transformation in not perfect. Then, replacing $\sigma_x$ with $e^{-i\theta\sigma x} = \cos\frac{\theta}{2}\mathbb{1} - i\sin\frac{\theta}{2}\sigma_x$ (with $\theta \simeq \pi$), the non-linear post-selection amplifies fluctuations of $\theta$ away from $\pi$. This eliminates the histories plagued by the paradox and retains only the self-consistent histories in which the time traveler fails to kill her grandfather (the unitary in the curve is 1 instead of $\sigma_x$), and the two output qubits have equal value: P-CTCs fulfill our self-consistency condition. [17]

This is consistent with the predictions of CCC. The probability that a time traveler will succeed in killing the man they find in the past is zero.

It is in this sense that the D-CTC consistency condition is radically different from the P-CTC consistency condition and CCC. The latter two require a single self-consistent history in which all events take place. The former requires consistency in the make-up of the collection of distinct parallel worlds which realize the mixed state $\rho_{\mathrm{CTC}}$.

This also gives a plausible answer to why entanglement isn't preserved through a D-CTC. The CTC-bound system that is potentially entangled with CR systems in its environment before it enters the future mouth of the wormhole is not numerically identical to the system that exits the past mouth of the wormhole. The qubit that emerges in the past has traveled from a different world. Preserving entanglement relations does not make sense in the context of the MSM model of time travel.

In addition to giving a relatively compelling solution to the Grandfather Paradox, the MWI analysis of time travel also provides a solution to the Knowledge Paradox, about which Deutsch is particularly concerned. He emphasizes the importance of a solution to the Knowledge Paradox repeatedly throughout his writings on CTCs:

> Knowledge paradoxes violate the principle that knowledge can come into existence only as a result of problem–solving processes, such as biological evolution or human thought. Time travel appears to allow knowledge to go from the future to the past and back, in a self-consistent loop, without anyone or anything ever having to grapple with the corresponding problems. What is philosophically objectionable here is not that knowledge-bearing artifacts are carried into the past—it is the "free lunch" element. The knowledge required to invent the artifacts must not be supplied by the artifacts themselves. [43]
>
> The real problem with closed timelike lines under classical physics is that

> they could be used to generate knowledge in a way that conflicts with the principles of the philosophy of science, specifically with the evolutionary principle. [1]
>
> It is a fundamental principle of the philosophy of science that the solutions of problems do not spring fully formed into the Universe, i.e., as initial data, but emerge only through evolutionary or rational processes. [1]
>
> This "near inconsistency", forcing a violation of the evolutionary principle, is a far more serious paradox than the "actual" inconsistencies of paradoxes 1–3. Those inconsistencies merely indicate that the initial data have one set of values rather than another, something which is true anyway, and starting from those values the subsequent evolution, though strange, does not contradict the philosophy of science. But because of the "near inconsistency" of [the knowledge paradox] the only permitted initial data cause an evolution that does contradict the philosophy of science. [1]

It is important to note that Deutsch emphasizes the fact that he considers the possibility of the Knowledge Paradox to be in conflict with principles from the philosophy of science. The evolutionary principle, which states that the existence of knowledge must be the result of problem-solving processes, is the most directly relevant principle. But why does Deutsch believe in it? Is it really a fundamental principle of the philosophy of science?

I will argue that Deutsch has a more fundamental principle in mind, which serves as a justification for the evolutionary principle. He is basing his justification of the evolutionary principle on the idea that there cannot be uncaused effects in the world. Everything must be explainable. Explanation plays an important role in his unified picture of science, articulated in *The Fabric of Reality*.

> Science seeks better explanations. A scientific explanation accounts for our observations by postulating something about what reality is like and how it works. We deem an explanation to be better if it leaves fewer loose ends (such as entities whose properties are themselves unexplained), requires fewer and simpler postulates, is more general, meshes more easily with good explanations in other fields and so on. [11]

Though he goes on to say that there is no necessary connection between explanatory power and truth, insofar as our aim is to develop a scientific understanding of the world, explanation is a necessary guide.

The existence of a Knowledge Paradox would represent unexplainable knowledge. This is in tension with a thoroughly scientific analysis of the possible existence of CTCs, and should therefore be avoided. Any model that will eliminate the unexplained presence of knowledge should be preferred. This is why Deutsch devotes so much effort to showing that D-CTCs solve the Knowledge Paradox.

## 5.4 Problems for Deutsch's Solution

It will be useful to have an example of a Knowledge Paradox scenario in hand to see how Deutsch's solution is supposed to work. A famous example involves a Shakespeare scholar building a time machine to bring his favorite edition of the great author's *Complete Works* back to Elizabethan London to have it autographed by Shakespeare himself at a time before his first play was staged. When he arrives, he asks where he can find Shakespeare, and is directed to the gutter in the alley behind the pub. He finds an illiterate inebriate passed out in a puddle, and throws his book to the ground in disgust before returning to his own time. When Shakespeare wakes, he finds the book, and goes on to plagiarize his life's work from it.

Deutsch adopts the position that the structure of parallel MSM worlds in his D-CTC model solves the problem of Knowledge Paradox. Since time travel into the past necessarily involves time travel into a different parallel world, the knowledge that the time traveler brings with him (in the form of the book) *also* comes from another world. In his original world, Shakespeare wrote his plays and sonnets. But in the world into which he travels, the *counterpart* of Shakespeare that he encounters has the luxury of simply copying them.

Deutsch argues that this avoids the paradox of getting "something for nothing" because, even though the counterpart of Shakespeare in the second universe didn't have to put in work to produce the plays for which he took credit, they were nonetheless the result of "genuine creative effort, albeit in another universe" [43].

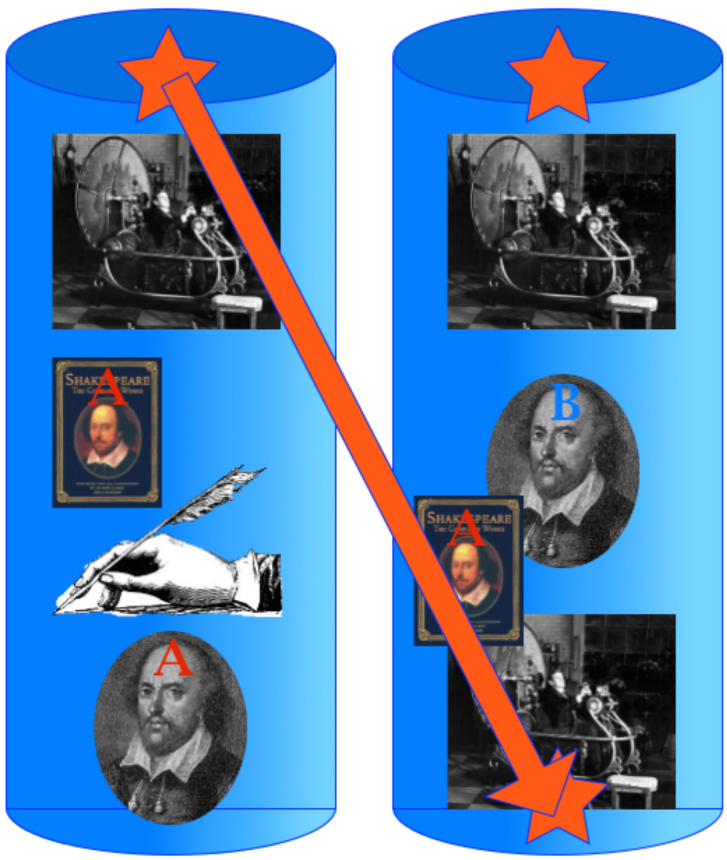
Deutsch is very concerned about the possibility of time travel allowing for knowledge to exist absent the kind of dynamic or rational processes we usually think give rise to it. However, with the resources afforded him by his version of the Everett interpretation of quantum mechanics, he seems to have a satisfactory solution.

I argue that this reliance on a metaphysical position to solve the Knowledge Paradox poses a unique problem for Deutsch. Committing himself to realism about the MWM means that he is committed to the existence of worlds in which any physically possible events happen, however improbable. This is an unusual, but unproblematic feature of MWI in most cases. However, I argue it presents a potentially fatal problem for the solution to the Knowledge Paradox offered by Deutsch.

The problem arises when we recognize that among the very improbable world histories MWI guarantees are actual are worlds which are in every way indistinguishable from worlds in which there is a genuine violation of the fundamental evolutionary principle for the existence of knowledge. Deutsch's commitment to the actuality of the many worlds of the Everett interpretation includes worlds that are in every way indistinguishable from the Knowledge Paradox worlds he is trying to avoid. In these worlds, the Shakespeare counterpart is genuinely getting something for nothing: a free lunch. Consider the following two cases:

In the first, a time traveler named Tim loves the works of Shakespeare, and decides to go visit him before he's written his first play. He follows a CTC back to late 16th century England. Of course, because of the way time travel works, Tim actually disappears from his own universe $A$, and appears in universe $B$. The man that he meets in London is not Shakespeare$_A$, but is Shakespeare$_B$. So there is no problem that Tim leaves his copy of the *Collected Works* and returns to his own time. Among the future possible timelines of universe $B$ is one that is in every other way (other than the fact that Shakespeare$_B$ is plagiarizing the plays and taking credit for them) indistinguishable from universe $A$. In 2121 Tim$_B$ is born, and at the exact same time that Tim$_A$ left *his* universe in a time machine, Tim$_B$ steps into his own time machine, destined for 16th century England (in universe $C$, of course).

Figure 5.3: Deutsch's solution to the Information Paradox. There is no "free lunch" because the work that Shakespeare$_B$ in the second world plagiarizes was written by Shakespeare$_A$ in the first world.




In the second case, in universe $X$ as the result of a random fluctuation, a man claiming to be Tim the time traveler appears in the alleyway behind a pub in 16th century England, looking for Shakespeare. He carries with him a book with the words "Complete Works of Shakespeare" legible on the front (though not *printed* per se, since they were the result of a random fluctuation). The man has a conversation with the layabout Shakespeare and leaves a book with him. Everything then proceeds in a way totally indistinguishable from the history of universe $B$. Shakespeare copies the plays out of the book, staging them periodically, and takes credit for them. In the year 2121, a boy named $\text{Tim}_X$ is born, and at the exact same time that $\text{Tim}_A$ and $\text{Tim}_B$ left *their* universes in a time machine, $\text{Tim}_X$ steps into his own time machine, destined for 16th century England. In this case, though, as a result of a fluctuation, he disappears into nothing, paying back the energy debt that allowed for the initial fluctuation.

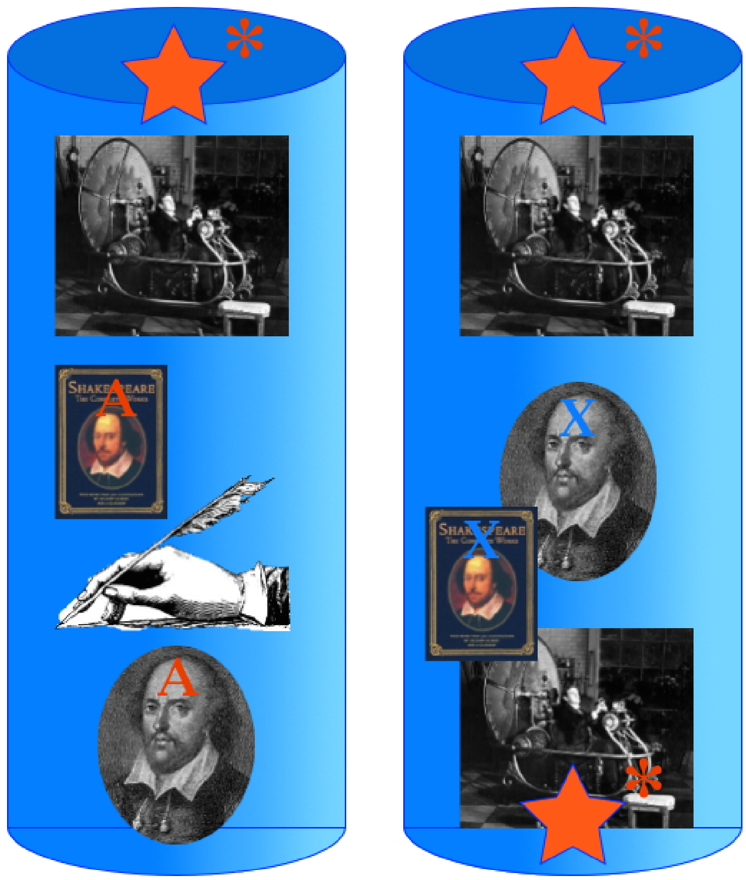
In the first story, however many iterations happen, the *Complete Works* were, at some point in their history, *actually* written by someone ($\text{Shakespeare}_A$). There is no free lunch. Deutsch's evolutionary principle is not violated.

However, in the second story, *no one* wrote the *Complete Works*. Yet the two worlds are indistinguishable in every way. Tim the time traveler in universe $X$, though he was the result of a fluctuation, could be imagined to have all of the memories that $\text{Tim}_X$ accrues over his life before he steps into the time machine.

The only difference between the two stories is that in the first, the time traveler is stipulated to be identical with an individual from another universe. However, there is no way that this could ever be verified.

Any experiments to test for the presence of a CTC would necessarily send our test particles into other universes, never to be seen again. There is a possibility that we could receive test particles *from* other universes, though it's not clear what

Figure 5.4: A pair of worlds guaranteed to exist by Deutsch's metaphysical picture. The two worlds are unconnected, but the sequence of events in them is entirely indistinguishable from those represented in Figure 2. The *Complete Works of Shakespeare*$_X$ was not authored by anyone, but was the result of a random fluctuation.




that evidence would establish, since we would have no access to the conditions under which the test particles were sent. And furthermore, for any conceivable data we could get that truly is the result of travel through a "gateway" from another universe, there is guaranteed to be another world in which indistinguishable evidence is gathered that is merely the result of a fluctuation.

Deutsch is careful to refer to the paradox under consideration as the "Knowledge Paradox", and not by the alternative, "Information Paradox". This potentially gives him some room to avoid this objection by claiming that the genuine paradoxical situations involve *knowledge*, whereas *The Complete Works of Shakespeare* that genuinely has no author, as in the worlds I point out, contains only *information*, and does not contain *knowledge*. We can come to have knowledge *of* that information (by studying the *Complete Works* in universe $X$), but Tim the time traveler did not possess knowledge of $\text{Tim}_X$'s life in the mid 2100s, and the book he gave to $\text{Shakespeare}_X$ contained merely information (and did so only accidentally). He draws this distinction between information and knowledge in [1]:

> "Knowledge is not the same thing as information, nor is it any function of information alone. There is as yet no quantitative measure of "knowledge" that could be incorporated into physics. However, it is reasonable to suppose that the requirement that a system contain no independent information (which is what the maximum entropy rule effectively says) might also imply that the system contains no independent knowledge." [1, 3204]

Deutsch may have the resources to distinguish between these two situations, but it seems to me that it comes at a significant cost. One of the primary goals of his model of CTCs was to eliminate the possibility of this paradox. However, the metaphysical position that he takes on to help build the foundation of his CTC model *necessitates* the belief that there are completely empirically indistinguishable histories from the ones he has tried to eliminate, in which there genuinely is a "free lunch". He can dispense with them by claiming that they do not contain real knowledge, and they are in principle distinct from the histories which *do*.

This can be seen as being motivated by the principle of the importance of explanation in a scientific theory. The existence of the *Complete Works of Shakespeare* in world $X$ is not the result of an evolutionary process, and is therefore merely information. Knowledge requires an evolutionary process, and so there must be an explanation for its existence. Deutsch's solution to the Knowledge Paradox offers an explanation for the existence of the *Complete Works of Shakespeare* in universe $B$—it's there because it was carried over by $\text{Tim}_A$ from universe $A$. Since there is no explanation for the existence of the *Complete Works of Shakespeare* in universe $X$, it does not count as knowledge.

## 5.5 Comments

If the above is the solution to the present challenge, it is unclear why he didn't just use this distinction at the outset to solve the puzzle of the Knowledge Paradox. He could easily have said that artifacts which are the result of a Knowledge Paradox situation contain only *information*, and therefore are unproblematic.

He would not have needed to rely on the trans–world explanation for the existence of future artifacts in the past. He could simply have claimed that any history in which a Knowledge Paradox exists, the relevant artifact contains only *information*, and not *knowledge* of how to create it.

It has been pointed out (e.g. [13]) that the P-CTC model does not rule out the Knowledge Paradox. In the context of the debate between the proponents of the two CTC models, this is seems to be used as a mark against P-CTCs. However, in light of the trouble that the D-CTC model has handling these scenarios, perhaps we should reassess whether we should require our CTC models to rule them out.

In the very same paper where Lewis introduced CCC, he writes of the possibility of Knowledge Paradoxes.

> But where did the information come from in the first place? Why did the whole affair happen? There is simply no answer. The parts of the loop are explicable, the whole of it is not. Strange! But not impossible, and not too different from inexplicabilities we are already inured to. Almost everyone agrees that God, or the Big Bang, or the entire infinite past of the universe, or the decay of a tritium atom, is uncaused and inexplicable. Then if these are possible, why not also the the inexplicable causal loops that arise in time travel? [19]

Given the extra metaphysical structure Deutsch needs to take on to solve the Grandfather Paradox, given that the additional benefit of the solution to the Knowledge Paradox is now somewhat cast into doubt, and given that there is a serious philosophical position that advocates for the acceptance of Knowledge Paradox effects, perhaps proponents of the D-CTC model should rethink his insistence on ruling out a free lunch.

It is perfectly consistent with a well-developed philosophy of science to believe that there are uncaused effects, as Lewis shows us. It's true that it would be a very strange world in which such a thing occurred. But that is not an argument against the possibility of a Knowledge Paradox obtaining.

# Chapter 6: On the Common Structure of the Primitive Ontology Approach and the Information-Theoretic Interpretation of Quantum Theory

## 6.1 Introduction

A recent series of papers by Valia Allori has brought the conception of fundamental physical theories based on a *primitive ontology* to the attention of a broader audience in the philosophy of physics community. The primitive ontology framework (PO) has been well known in the debates about the interpretation of quantum mechanics since it was introduced by Allori's frequent collaborators in the 1990s (see [50] [51] [52] [53]). But Allori's recent clear presentation of PO (see [54] and [55]) has made it more amenable to broader application. In this paper, we will discuss the features of PO, and analyze the quantum-information theoretic interpretation—a competing interpretation of quantum theory–in its terms. The comparison between the two approaches is illuminating, particularly because PO provides a framework in which significant similarities can be seen between the two seemingly very different ways of conceiving of the quantum world.

Several authors have developed interpretations of quantum theory that are broadly information–theoretic (see e.g. [56] and [57]). I will focus here on the version due to Bub and Pitowsky, which was first fully formulated in [31], but had its origins in earlier work of Clifton, Bub, and Halvorson [58], Bub [59] and [60], and Pitowsky [61]. This quantum information–theoretic interpretation (QITI) is formulated fundamentally in terms of information-theoretic constraints on the possibility of correlations between events. It is argued that a small number of such constraints pick out the Hilbert space as the fundamental space in which the theory is formulated, which in turn imposes conditions on the possibilities of correlations between events. These information-theoretic principles have physical motivation, as they represent various "no-go" theorems of quantum mechanics. The interesting feature of QITI, though, comes in considering these kinematical principles to be the fundamental formulation of quantum theory. What quantum theory tells us about the structure of reality, according to this way of thinking, is that it conforms to a non-Boolean underlying event space, out of which an effectively classical macroscopic world can emerge.

It should be immediately obvious that there is some tension between this conception of the fundamental formulation of quantum theory, and the more straightforwardly realist approaches, including PO. However, we will argue that they are similar in that they both reject a central tenet of the various *wave function ontology* approaches. By analyzing QITI in terms of PO, however, the ways in which they differ will also be clear. This analysis, we argue, helps bring to light an important sense in which the commitments of QITI are underspecified. Several possible ways to complete the interpretation are considered, and it is argued that the route seemingly most in line with the rest of Bub and Pitowsky's approach leaves QITI such that it would fail to qualify as a theory, according to PO.

## 6.2 Primitive Ontology

PO is a framework for the formulation of candidate fundamental physical theories. The most salient feature of PO is its insistence on clarity and perspicuity with respect to the ontological commitments of the physical theory. Each theory is explicit from the outset about its *primitive ontology*. That is, each proposed theory begins by stipulating what the theory is about. A theory must be about the behavior of localized material entities, on this view. In this respect, it is similar to Bell's focus on the "beables" of a theory (see [62] and [63]).

PO imposes additional constraints on the primitive ontology of a fundamental physical theory. Crucially, the elements of the primitive ontology must exist in three-dimensional physical space. It is only in this way that they can conceivably count as the fundamental constituents of everyday physical objects. The theory is therefore about the evolutions of, and interactions between, these entities, which gives rise to the manifest image of the world we experience.

> The aim of a fundamental physical theory is, we believe, to describe the world around us, and in so doing to explain our experiences to the extent of providing an account of their macroscopic counterparts, an account of the behavior of objects in 3-space. Thus it seems that for a fundamental physical theory to be satisfactory, it must involve, and fundamentally be

> about, 'local beables' [...]. [52]

Therefore, in this framework, only certain of the interpretations of quantum theory that are usually considered to offer solutions to the measurement problem count as candidate fundamental physical theories. The most obvious fit with the PO framework is Bohmian Mechanics. Its primitive ontology—namely, particles with definite positions—is stipulated from the outset. Although the wave function is part of the ontology of the theory, it is secondary to the material particles.

> [E]ven if the primitive ontology does not exhaust all the ontology, it is the one that makes direct contact between the manifest and the scientific image. Since the primitive ontology describes matter *in the theory*, we can directly compare its macroscopic behavior to the behavior of matter *in the world of our everyday experience*. Not so for the other non-primitive variables [including the wave function], that can only be compared indirectly in terms of the way in which they affect the behavior of the primitive ontology. [54]

The GRW theory can also be formulated in the PO framework, so long as an ontology in three-dimensional space is adopted. Therefore, the $\text{GRW}_f$ "flash" ontology version is consistent with PO, as is the $\text{GRW}_m$ mass-density version.

The "bare" version of the theory, or $\text{GRW}_0$, is not consistent with PO, since it holds that the wave function is the full story of the ontology of the world. In this case—as with all interpretations that take the wave function to be among the fundamental elements of the ontology—the space in which the wave function evolves in accord with the dynamics is $3N$-dimensional configuration space.[1]

The problem of the correspondence between the ontology in the fundamental $3N$-dimensional configuration space and the macroscopic three-dimensional world of everyday experience has been well expressed elsewhere (see [64] and [65]), but it takes on an interesting character in the context of PO. The problem isn't simply one of correspondence between particular dimensions of the configuration space and the identity of particles in three-dimensional space. Rather, it is that, in the context of the PO, it is impossible for three-dimensional macroscopic objects to be *made up of* an ontology existing in an altogether different space. It is a gap in the ontology, not merely an underspecification of the correspondence between the two spaces. Allori et al. characterize such theories as ones "for which there exists no arrangement of stuff in physical three-dimensional space at all" [52].

This framework also rules out the Everett interpretation for the same reasons. However, Allori proposes an alternative version of the Everett interpretation that supplements the standard version with a primitive ontology. In order for the Everett interpretation to be formulable in PO, it needs to, like GRW, adopt either a "flash" or a mass-density ontology [54]. The "bare" version of the Everett interpretation (which Allori calls $MW_0$) fails to be a candidate fundamental physical theory, because it does not have an ontology that exists in ordinary three-dimensional physical space.

[1]It is important to note that since the $GRW_0$ theory does not include particles in three-dimensional space in its picture of the world, the space in which the wavefunction evolves is not actually a configuration space of $N$ particles. However, the space on which the wave function is defined has a dimensionality equal to $3N$, and is effectively identical to a configuration space of $N$ particles.

The fact that PO is not consistent with the standard Everett interpretation shows that PO deviates in a significant way from the interpretations of quantum theory that have traditionally been taken to be realist. The difference can be located in the relationship presumed to hold between the mathematical structures of the theory and its ontology. The traditional scientific realist takes the mathematical objects in the theory to somehow represent elements of reality.

The following passage from David Wallace's *The Emergent Multiverse* is a suitable representative of the motivations of the realist wave function ontology position. He begins with a simple statement of scientific realism:

> [W]hat scientific theories do is give us information about the the universe—what sort of things are in it, about how they are structured, about how they come into existence and interact and change and disappear. [66]

He then argues against those who would claim that quantum mechanics must be different in this respect:

> [N]either the mathematical formalism of quantum mechanics, nor the standard conception of science is in any need at all of modification. Rather: the unmodified quantum theory can be taken as representing the structure of the world just as surely as any other theory of physics. [66]

What differs among the different standard realist interpretations is how much modification quantum theory must undergo in order to successfully represent the structure of the world and the fundamental entities in it. But what is shared among all of them is the idea that fundamental physical theories act as a guide to our understanding of what those entities and structures are. Physics is a guide to metaphysics on this conception. And in particular, each realist interpretation includes some commitment to what the fundamental ontology of the world is. The wave function corresponds, in these interpretations, to an element of reality.

I argue that this is the major point of departure for PO. As Allori emphasizes in [55], the primitive ontology approach is partially constitutive of a different understanding of what fundamental physical theories are, and how they function. The primitive ontology approach does not consider the ontology of the world to be determined by the structures in the mathematical formulation of the theory.

> The starting idea is that when a scientist proposes a fundamental physical theory, she already has in mind what the theory is fundamentally about: the primitive ontology. This is the metaphysical role of the primitive ontology, it tells us what the world is made of according to the theory. [55]

With respect to the idea that the mathematical objects of the theory represent entities or structures in the world, she says

> [T]here is already a natural interpretation for each mathematical object, namely, the one the proponent of the theory intended to give them! The scientists choice of what physically exists in the world will more or less automatically determine the mathematical object to represent it. [55]

Unlike the traditional realist interpretations, the ontology of the theory is not determined by its mathematical structure, and therefore the theory itself is not a guide to the underlying metaphysics. Rather, the ontology is determined at the outset by the author of the theory. She argues that the wave function ontology picture gets this backward.

> [T]he wave function ontology view is misguided: it assumes the fact that the mathematical formalism of a theory can be interpreted a posteriori, whereas it was fixed a priori by the physicist when she formulated the theory. [55]

The emphasis of PO is that fundamental physical theories are not to be understood as a guide to fundamental ontology of the world. Rather, it holds that the way to conceive of a fundamental physical theory is as an account of how a given posited ontology underwrites, or causes, or explains the behavior of observable objects.

Allori presumably doesn't consider this framework to amount to a demotion of the importance of the ontology of the theory. This is evidenced by her claim that differing primitive ontologies amount to the scientist offering a "metaphysical hypothesis" around which the theory is developed [55]. There is still space on this account to believe that there is a connection between the primitive ontologies of our best theories and entities and structures in the world.

However, PO does allow one the leeway to prefer certain proposed primitive ontologies for extra-theoretical reasons. For example, Allori insists that the primitive ontology for any candidate quantum theory be entities that exist in three-dimensional space.

> A primitive ontology in the familiar three-dimensional space evolving in

> time (or a space-time primitive ontology) is the natural metaphysical choice, if the theory with such a primitive ontology can be empirically and explanatorily adequate. [55]

She goes on to say

> [T]hey are quantum theories in which, as in classical theories, there is stuff in space-time, and we can develop a clear explanatory scheme, along the lines of the classical one, to account for the macroscopic world. [55]

This focus on a theory being fundamentally understood as an account of a posited ontology underwriting the manifest image is one similarity that PO shares with QITI. Neither conceives of fundamental physical theories as giving guidance to metaphysics. Rather, they conceive of fundamental physical theories to primarily be about accounting for how the macroscopic manifest image supervenes on the quantum world.

## 6.3 Quantum Information-Theoretic Interpretation

The quantum information-theoretic interpretation of quantum theory is the outgrowth of results from two independent lines of inquiry of Bub and Pitowsky. Bub's earlier work in collaboration with Clifton and Halvorson [58], from which the CBH theorem resulted, forms the foundation of the interpretation. He later expanded on the implications of the theorem in [59] and [60]. In those papers, he invoked a distinction, due to Einstein, between principle and constructive theories, to argue that the fundamental formulation of a physical theory need not make reference to an underlying ontology and dynamics.

Pitowsky's argument from [61] introduced the idea of reconceptualizing quantum theory as being about the constraints imposed on the correlations between events implied by the Hilbert space formalism. The combination of the two projects allowed them to formulate a full-fledged interpretation of quantum theory that offered a solution to the measurement problem [31].

The CBH theorem was a breakthrough in the quantum information literature, because it seemed to offer a way of understanding the content of quantum theory based on physically plausible principles. These three principles—No Signaling, No Broadcasting, and No Unconditionally Secure Bit Commitment—when suitably translated into information-theoretic constraints on the probabilities of outcomes of experiments on isolated systems, come very near to uniquely picking out quantum theory from among a general space of possible probabilistic theories.

In [59] and [60], Bub argued that the CBH theorem shows that quantum theory is really a theory about the possibility of representing and manipulating information. If information is taken as a new physical primitive, then the three information-theoretic constraints of the CBH theorem suggest a path to understanding quantum theory as a principle theory, which has no need for reference to an underlying ontology.

> The question: What is information in the physical sense (if its not about the properties of physical stuff)? should be seen as like the question:

> What is a field in the physical sense (if it is not the vibration of a physical medium)? The answer is something like this: Quantum mechanics represents the discovery that there are new sorts of information sources and communication channels in nature (represented by quantum states), and the theory is about the properties of these information sources and communication channels. [59]

It is possible, he argues, to give a mechanical story, based on ontological primitives and dynamics, but it can have no additional empirical content over the principle-theoretic formulation.

Pitowsky's 2006 paper [61] argues that quantum theory should be thought of as a new theory of probability. Like classical probability theory, it consists of a space of possible events, and a measure over it. In the quantum case, the space of possible events is identified with the lattice of the closed subspaces of Hilbert space, which Pitowsky says "represents the elements of reality in the theory". Pitowsky argues that conceiving of quantum theory in this way frees one from having to worry about the measurement problem as it is usually formulated. There is no possibility of explaining the particular outcome of an experiment on this view. The event space defines the possible outcomes of measurements, and the quantum state is taken to be an epistemic feature of the theory, encoding the experimenter's beliefs. Measurement outcomes—macroscopically observable outcomes of experiments—are taken as basic elements of the theory. These outcomes are systematic—meaning that the same measurements on similarly prepared systems will produce a stable set of outcomes—and are consistent with the structure of the closed subspaces of Hilbert space.

In "Two Dogmas About Quantum Mechnics", Bub and Pitowsky unify the elements of their previous work to create QITI. They begin by identifying the two assumptions they consider to be responsible for the widely-held belief that the quantum measurement problem has not been decisively solved. The two assumptions are (1) that measurement should never be included as an unanalyzable primitive in a fundamental physical theory, and (2) that the quantum state has some ontological significance as a truthmaker for propositions about the occurrence or non-occurrence of events. They argue that the rejection of these dogmas allows them to divide the measurement problem into two parts. The "big" measurement problem is the problem of giving a dynamical explanation of why particular measurements have particular definite outcomes. The "small" measurement problem is the problem of explaining how the seemingly classical macroworld in underwritten by the non-Boolean quantum event space. They claim to show that they can dismiss the former as a pseudo-problem, and they can solve the latter [31].

The argument against the need to address the "big" measurement problem proceeds as an argument from analogy. They argue that the Everett interpretation gets around explaining why particular experiments have particular definite outcomes by denying that experiments have definite outcomes at all. They identify the elements of the Everett interpretation that they believe qualify it as a realist interpretation that solves the measurement problem. They then argue that QITI shares all of these features.

The elements of the Everett interpretation that justify the claim that it solves the measurement problem are as follows: (1) a weighted structure of effectively classical worlds, which emerge via decoherence, (2) an argument that agents can be uncertain and have different preferences about futures states of the world, and (3) a claim that the agents' preferences should converge on the weights of the branches. These three elements together succeed in "saving the appearances" of a classical macroscopic reality.

QITI, while maintaining that experiments have particular outcomes, denies that a dynamical explanation of those facts is fundamental. However, by demonstrating a similarity between QITI and the Everett interpretation with respect to these three points, they argue that QITI has equal claim to being a realist interpretation with a solution to the measurement problem. They argue that a solution to the "big" measurement problem is not a necessary feature of a realist interpretation. On QITI, the "big" measurement problem is a pseudo–problem, and a realist interpretation need not offer a solution to it. Point (1) is the "small" measurement problem, which Bub and Pitowsky solve in a similar way to the Everett interpretation, via decoherence. Point (2) is a feature of QITI, since they take the quantum state to represent the epistemic situation of the experimenter. Point (3) is achieved by using Gleason's theorem.

They appeal to Einstein's distinction between principle and constructive theories, and argue that the traditional realist interpretations are all to be understood as constructive versions of quantum mechanics, whereas their account is a principle version. They take the fact Einstein's principle account of Lorentz covariance (special relativity) was preferred to Lorentz's own constructive account to be encouraging evidence that a realist principle physical theory can supplant a constructive version. The fact that there was a possible dynamical explanation of Lorentz covariance (namely, Lorentz's own dynamical account) was taken to justify interpreting special relativity realistically.

Similarly, quantum mechanics has the resources to explain the outcome of any particular experiment dynamically. The process of decoherence ensures that the interactions that give rise to entangled states comprised of quantum systems and measuring devices will yield effectively classical macroscopic effects. That is to say, the dynamics of quantum mechanics is consistent with the classical probability space of macroscopic measurement outcomes.

This shows that the non-Boolean structure of the quantum event space is consistent with the effectively classical event space of macroscopic outcomes. However, the dynamical explanations of particular outcomes are not possible, since macroscopic events are taken as basic. Therefore, an account which supplements quantum mechanics with an underlying ontology, in order to give dynamical explanations, is less fundamental than QITI.

We argue that their focus on the "small" measurement problem as the more fundamental of the two is evidence of a certain parallel with the primitive ontology approach. The primary question for a physical theory on both conceptions is how it can underwrite the manifest image of the macroworld, not what metaphysical picture quantum theory requires us to accept about the elements of reality.

The traditional realist interpretations of quantum theory take the "big" measurement problem to be centrally important. Each of them offers a solution to it, and that solution crucially features a commitment to one fundamental ontology or another. Bohm's theory, for example, answers the "big" measurement problem by including particles with definite positions among the fundamental ontology, which determine the outcomes of experiments. It is the rejection of the idea that the theory needs an underlying metaphysical picture that allows Bub and Pitowsky to dismiss the "big" measurement problem.

## 6.4 Common Structure in PO and QITI

In this section, we will argue that there are two important similarities between PO and QITI, that set them both apart from the traditional realist wave function ontology approaches. The first is that they both reject the idea that the mathematical objects in the theory should be seen as representing entities in reality. As discussed in Section 2, this standard scientific realist move is motivation for taking the wave function seriously as an element of reality. In both PO and QITI, however, they deny that the wave function is the right kind of mathematical object to possibly represent a fundamental enitity.

Of course, they both agree that there is something to be learned about the world from the mathematical features of quantum theory. In the PO case, Allori et al. suggest considering the wave function to be law-like, and to be a non-primary element of reality that is only discoverable by virtue of its action on the primitive ontology. The QITI case considers the structure of the Hilbert space to be the space of possible events. But in both cases, the mathematical objects of the theory are not a guide to the underlying ontology.

That is to say, both PO and QITI reject Bub and Pitowsky's second dogma, that the quantum state must be taken as representative of an element of physical reality. PO rejects the possible ontological *fundamentality* of the wave function. QITI rejects that the wave function could be an element of reality at all.

This is an explicit rejection of the wave function ontology approaches of the Everett interpretation and $GRW_0$. PO holds that these are not candidate fundamental physical theories because they lack the right kind of ontology. QITI considers them to be non-fundamental because they add structure to quantum theory, without any gain in empirical content.

The second respect in which PO and QITI are similar is that they prioritize explanations of the emergence of the manifest image from the quantum world. On these views, the goal of a fundamental physical theory isn't as a guide to the underlying metaphysics of the world. Rather, its primary purpose is to give an explanation of the effectively classical macroscopic world of everyday experience. However, they differ on how to achieve this, and what would count as a successful theory with respect to this criterion.

PO argues the only way this can be accomplished is by telling a story of how the material entities that constitute macroscopic objects behave. Otherwise, the theory wouldn't be *about* anything at all.

What is wrong with $GRW_0$, the bare version of GRW, which involves

> just the wave function and nothing else? Why does one need a PO at all? Our answer is that we do not see how the existence and behavior of tables and chairs and the like could be accounted for without positing a primitive ontology—a description of matter in space and time. [52]

QITI, on the other hand, holds that demonstrating the dynamical emergence of an effectively classical event space sufficiently underwrites the existence of the manifest image of everyday experience.

> The analysis shows that a quantum dynamics, consistent with the kinematics of Hilbert space, suffices to underwrite the emergence of a classical probability space for the familiar macro-events of our experience [...]. The explanation for such nonclassical effects as the loss of information on conditionalization is not provided by the dynamics, but by the kinematics, and given 'no cloning' as a fundamental principle, there can be no deeper explanation. In particular, there is no dynamical explanation for the definite occurrence of a particular measurement outcome, as opposed to other possible measurement outcomes in a quantum measurement process—the occurrence is constrained by the kinematic probabilistic correlations encoded in the projective geometry of Hilbert space, and only by these correlations. [31]

They argue that the existence of possible dynamical explanations of the outcomes of the experiments (including the wave function ontology and primitive ontology approaches, which they claim all add structure to the quantum formalism) serve as a proof of the consistency of their account. But it is important to note that these dynamical explanations are *not* fundamental.

## 6.5 Comments

The QITI denies the fundamentality of an underlying ontology, and is therefore open to the same critiques from the PO approach as the "bare" wave function ontology. Without an underlying ontology, it is difficult to understand what the theory claims macroscopic objects like tables and chairs are *made of.* In PO, the proposed ontology constitutes the objects of everyday experience, and so explains them. Bub and Pitowsky explicitly reject the notion that explanation of the state of a macroscopic system is necessary, but in so doing they seem to be demoting the idea of an underlying ontology altogether. And without a primitive ontology, QITI fails to qualify as a candidate fundamental physical theory, according to PO.

But QITI also claims to be a realist interpretation that solves the measurement problem. Perhaps there is an implicit ontology underwriting the view. After all, how could information be a fundamental element of reality if it was not being carried by some material entity?[2] As they say

> The possibility of a dynamical analysis of measurement processes consistent with the Hilbert space kinematic constraints justifies the information-theoretic interpretation of quantum mechanics as realist and not merely a predictive instrument for updating probabilities on measurement out-

[2]It is worth nothing here that Bub and Pitowsky disavow the 'It–from–bit' position, which claims that immaterial information gives rise to the material world.

> comes. [31]

What elements of reality could the features of the theory be representing if not an underlying ontology?

I will consider four possible ways that QITI could be supplemented such that it would count as a candidate fundamental physical theory according to PO. The possible ways QITI could flesh out their ontology that I will consider are (1) a macroscopic ontology, where outcomes of experiments constitute the primitive ontology, (2) an event ontology, (3) a particle ontology in 3-d space, with an indeterministic dynamics, and (4) the principles that characterize the event space as the elements of reality.

With respect to option 1: It seems as though Pitowsky is making this claim in [61] by calling measurements, and measurement outcomes, unanalyzable. It seems that in that paper he holds that there is a definite distinction between the quantum and classical domains. Allori suggests that a position like this would be amenable to treatment in the PO framework.

> It is interesting to note that even the orthodox quantum theory [...] involves such a dual structure: what might be regarded as its primitive ontology is the classical description of macroscopic objects, including in particular pointer orientations, while the wave function serves to determine the probability relations between the successive states of these objects. [55]

However, Pitowsky also claims in [61] that there are fundamental particles (see option 3 below), and neither of these positions seems to survive to the formulation of QITI in [31].

With respect to option 2: QITI seems to make this claim at times, as when they describe the kinematical constraints on correlations as being part of the fundamental formulation of the theory, and Hilbert space as a space of events. However, this would give rise to a correspondence problem—similar to the one encountered by the wave function ontology positions—between the kinematical constraints in Hilbert space, and events in everyday three-dimensional physical space.

With respect to option 3: Pitowsky explicitly makes this claim, saying in [61]

> What is real in the quantum world? Firstly, there are objects—particles about which the theory speaks—which are identified by a set of parameters that involve no uncertainty, and can be recorded in all circumstances and thus persist through time and context. [61]

There are two problems with this, however. The first is that it seems to be in direct contradiction to other claims made elsewhere in the course of the argument. For example, he argues that the structure in quantum theory that represents elements of reality is the lattice of closed subspaces of Hilbert space, which he identifies as a space of possible events. Secondly, the correspondence problem described above becomes more acute in this case. Since the wave function is not part of the ontology, and therefore does not act on the material particles in any way, it is difficult to see how constraints on correlations in an abstract event space can *cause* material particles in three-dimensional physical space to behave in particular ways such that the disallowed correlations do not obtain. In any case, the explicit talk of physical particles underlying the QITI interpretation is absent in its fully developed form in [31].

With respect to option 4: The statement of the virtues of the QITI interpretation in [31] includes the following passage:

> The possibility of a dynamical analysis of measurement processes consistent with the Hilbert space kinematic constraints justifies the information-theoretic interpretation of quantum mechanics as realist and not merely a predictive instrument for updating probabilities. [31]

The "possibility of a dynamical analysis of measurement" to which they are referring is the existence of the dynamical explanations of measurements available to Bohmian Mechanics, GRW, and Everett. These are seen as demonstrative of the fact that the quantum dynamics is consistent with the kinematical constraints encoded in the Hilbert space structure. Any physical evolution can be so dynamically explained. What QITI takes this to mean is that the correlations required by the Hilbert space can arise, through the process of decoherence, from the quantum dynamics. But the ontological commitments of these interpretations are not thought to be indicative of a more fundamental formulation of quantum theory. That is to say, any explanation that can be given about the outcome of a particular experiment by reference to the ontology and the dynamical evolution of the states of the system over time, is not formulated in the most fundamental version of the theory.

The condition in PO that any candidate fundamental physical theory be formulated in terms of the material entities in three-dimensional space, and the dynamics describing their behavior, entails that any theory consistent with PO would be considered a non-fundamental formulation by QITI.

So what is the ontology of QITI? Bub and Pitowsky address this question by providing an explanation for what elements of reality supply the supervenience base for macroscopic objects.

> On the information-theoretic interpretation, no assumption is made about the fundamental 'stuff' of the universe. So, one might ask, what do tigers supervene on? [...] In the case of the information-theoretic interpretation, the 'supervenience base' is provided by the dynamical analysis: tigers supervene on events defining a two-valued homomorphism in the emergent Boolean algebra. [31]

They go on to explain

> The dynamics does not describe the (deterministic or indeterministic) evolution of the two-valued homomorphism on which tigers supervene to a new two-valued homomorphism (as in the evolution of a classical state). Rather, the dynamics leads to the relative stability of certain event structures at the macrolevel associated with the familiar macrosystems of our experience, and to an emergent effectively classical probability space whose atomic events are correlations between events associated with these macrosystems and microevents. [31]

There is no commitment to an underlying ontology in QITI. The dynamical equations of motion are not understood as evolving physical systems in particular states into other particular states. Rather, they evolve the "whole structure of events with probabilisitic correlations in Hilbert space" [31]. The theory is most fundamentally formulated in terms of the constraints on correlations of events in an abstract space. The theory is not fundamentally about the behavior of a particular ontology that constitutes all matter in the physical world. In this sense, QITI fails to qualify as a candidate fundamental physical theory according to PO.

However, it is interesting to note that QITI can be seen as characterizing the features that all quantum theories (in the PO sense) share. That is to say, that which makes the various quantum PO theories *quantum*, is their shared structure of possible events. Each offers a different explanation for why that event space is the correct one—an explanation based on the existence of a particular primitive ontology and a story about the dynamics. But QITI can be understood as offering an information-theoretic way of thinking about the shared features of all candidate fundamental formulations of quantum mechanics.

# Chapter 7: Conclusion

## 7.1 Overview

Nonlinearity, like that introduced by the presence of a Deutsch–type closed timelike curve, leads to unusual physical behavior, even by the standards of quantum mechanics. Although there is no current reason to believe that there are CTCs in our universe, the study of these extensions of quantum mechanics helps illuminate otherwise dim corners of the theory. Distinctions that make no difference in the context of the normal quantum framework can lead to different predicted behavior in a more general framework.

D-CTCs have been the central focus of this dissertation. While they represent a very peculiar extension of quantum theory, their study is no less valuable than the more general cases. This is due in part to the fact that CTCs have been shown to be consistent with General Relativity. Although we have no positive evidence that would lead us to believe any such thing exists, if GR is true of our world, CTCs could obtain. Deutsch's model for the behavior of quantum systems in the presence of a CTC is only one proposal among several. But it is the oldest and arguably most influential. The D-CTC model, especially in its popular presentations (e.g. [43] and [11]), is surely responsible for the common conception that quantum mechanics provides a justification for multiple–timeline solution to the paradoxes of time travel.

However, as I argued in Chapter 4, it is not quantum mechanics itself that can solve the Grandfather Paradox. Deutsch's solution requires a commitment to an additional ontology so replete with worlds that it makes the standard Everett interpretation look conservative by comparison. These worlds are not pre-existing elements of the normal MWI branching structure, of which Deutsch is making use. Rather, they only arise as objects in need of interpretation after the acceptance of Deutsch's consistency condition on $\rho_{\text{CTC}}$. The presence of a system in a mixed state bound to the CTC is necessary for Deutsch's solution to the Grandfather Paradox. But the fact the system is in the exact state to avoid the paradox is unexplainable by ordinary quantum mechanics. The explanation Deutsch offers relies on his interpretation of the mixed state as representing the existence of worlds beyond those present in the Everett branching structure. Without reference to these MSM worlds, the D-CTC model would allow for additional consistent solutions to certain GP situations that are inconsistent with Deutsch's story. The ontology of MSM worlds is a necessary component of the model, which ensures that it makes the predictions Deutsch claims and not others. The D-CTC model relies crucially on the existence of a multiverse of parallel interacting worlds, and a structure of relations between them that comes into existence in the presence of a CTC. Since the model is supplemented by structures that go significantly beyond those of ordinary quantum theory, which play an ineliminable role in its predictions and explanations, it does not represent a quantum solution to the paradoxes of time travel.

In Chapter 5 I argue that the D-CTC model's purported solution to the knowledge paradox is equally problematic. The D-CTC model employs a consistency condition of a significantly different kind than its two main rivals. While both the classical consistency condition and the consistency condition found in the P-CTC model apply to a single timeline of events, the D-CTC consistency condition applies to the multiple timelines Deutsch considers actual. His commitment to the reality of the MWM branching structure of the Everett interpretation, along with the more non-standard MSM structure discussed in Chapter 4, undermines his solution to the Knowledge Paradox. In some of these real worlds, events in every way empirically indistinguishable from genuine instances of Knowledge Paradoxes will obtain. His only recourse is again to the extra structure that he claims is introduced by the presence of a CTC to differentiate between worlds in which there is merely the appearance of a true Knowledge Paradox, and worlds in which the Knowledge Paradox is solved by a connection via a CTC to another world in which the evolutionary principle was respected.

If we did have access to a D-CTC, there is an argument that suggests that we could use it to signal. This argument is the focus of Chapter 3. The signaling is achieved by using the BHW circuit—which perfectly distinguishes the four nonorthogonal BB84 states—in conjunction with an entangled pair of particles. However, there has been some debate about whether this predicted result should stand. Some argue that the prediction is inconsistent with the relativity theory. In Chapter 2 I argue that, in general, relativistic considerations are not sufficient to rule out instantaneous signaling. I distinguish between Superluminal Information Transfer—which arguably *is* affected by relativistic arguments, since it requires a physical carrier of information traveling faster than the speed of light—and Nonlocal Signaling. NS is the result of purely quantum phenomena, and therefore classical notions of causation may not apply. For example, the Principle of Continuity fails. Timpson argues that we can make physical sense of information transmission in which there fails to be a token of information continuously traversing the space between the two communicating parties. I argue that relativity doesn't rule out this kind of phenomenon in the case where there is a privileged reference frame, or in the case where there is a consistency condition to ward off paradoxes. Since the debate over signaling in Chapter 3 takes place in the context of a discussion of the D-CTC model, the latter condition holds.

In Chapter 3 I also examine the differences in fundamental assumptions that would lead one to conclude one or the other thing with respect to signaling. Whether there can be top–down principles that overrule the predicted behavior of localized systems. Deutsch certainly didn't think so, and he was clear that finding a way around conditions like this was part of his motivation for developing the D-CTC model in the first place. I suggest the QIT as an approach is fundamentally this kind of enterprise. I contrast it with the more metaphysically oriented interpretations of quantum theory, which are mainly constructive. I suggest that since Deutsch's D-CTC model makes substantial metaphysical assumptions on the level of ontology, it is not properly understood as being consistent with a principle–theoretic approach. Therefore, its fit with QIT is undermined.

In Chapter 6, I expand upon the distinction between principle and constructive formulations of quantum theory, arguing that, at least in one case, they have certain features in common. However, the differences may be more relevant for the question of the efficacy of each approach's attempts to shore up the foundations of quantum theory. The Primitive Ontology framework is a general schema for ontic approaches to quantum foundations. Although some of the main contenders for a metaphysical interpretation of quantum theory are inconsistent with PO (including MWI), the features relevant for comparison with QIT are shared by all ontic quantum theories. The comparative project in Chapter 6 represents the beginning of a larger research project in which the potential for foundational progress of QIT and the ontic approaches are explored. I now turn to describing the future directions for research indicated by this dissertation project.

## 7.2 Future Directions for Research

The analysis of the D-CTC model was motivated by the fact that it is a point of contact between the QIT approach and the metaphysical commitments of the constructive, or ontic approaches to the foundations of quantum theory.

The ontic approach to the foundations of quantum mechanics traces its origins back to Einstein's position in his famous debate with Bohr about the interpretation of the EPR state [32]. Einstein himself considered the possibility of the EPR state in quantum mechanics to be evidence that quantum mechanics was an incomplete account of the natural world, and would someday be supplanted by a more complete theory. The argument from the Einstein, Podolsky, and Rosen paper (from which the state under consideration takes its name) purports to show that a realist interpretation of the predictions of quantum theory is incompatible with the idea that quantum mechanics is complete. That is, if you are a realist, you will be forced to accept that quantum mechanics is an incomplete description of physical reality.

However, Einstein and his collaborators famously made two substantial assumptions in this argument. The criterion of reality they relied upon in the argument requires that physical systems be both separable and local. Separability can be understood in the following way: if two systems $A$ and $B$ are distant in space, then $A$'s elements of reality can be identified and analyzed in isolation from $B$'s. Locality says that, if $A$ and $B$ are separated in space, any intervention performed on system $A$ will only have effects on system $A$. That is to say, causes can only have physical effects in their immediate local area—there is no nonlocal influence.

It was pointed out by J. S. Bell [62] that the EPR argument made these assumptions, and that it was possible to hold a realist interpretation of quantum theory, which considered the theory to be a complete description of the physical world, so long as one accepted that the condition of locality failed. In fact, the content of Bell's famous theorem proves that any complete realist theory that is consistent with the predictions of quantum mechanics will necessarily include nonlocality.

Bell's theorem re-opened the door for a serious exploration of the possibilities of a realist interpretation of quantum mechanics. Although there are many disagreements among the philosophers and physicists pursuing this line of inquiry, they all share the feature that they take the metaphysical principle of scientific realism to be prior to other considerations. As a result, most interpret the quantum wavefunction as being among the ontic elements of reality.

The various realist interpretations of quantum mechanics, including the de Broglie-Bohm pilot wave theory, GRW theory, and MWI, are all part of the ontic, or metaphysical approach. They all prioritize questions about the fundamental elements of reality (which Bell calls the "beables" of the theory). According to this approach, to solve the foundational issues in quantum theory, one needs to establish what the beables of the theory (interpreted as referring to elements of reality) are. In simple terms, the goal of this approach is to discover what the "stuff" the world is made of is, as a definite answer to that question along the lines suggested by any of the alternatives listed above, would solve the foundational puzzles of quantum mechanics.

I want to further explore both sides of this issue. Firstly, in what ways does the QIT approach (and others like it, including QBism) contribute to our understanding of the foundations of quantum theory? I have no preconceptions about the outcomes of this inquiry, though I do believe that the Measurement Problem will feature as a central nexus in the debate. The MP is solved by the metaphysical interpretations of quantum theory by positing some ontological picture of reality that is consistent with a definite microphysical picture and a definite macrophysical picture. QIT must explain away the importance of the need for an ontology to solve the measurement problem, as Bub and Pitowsky attempt to do in [31].

Secondly, there is a question as to whether it is possible that a fundamental physical theory can be formulated in terms of principles. It requires a commitment to a denial of ontology as fundamental. Would it be the case that a good reason to accept some particular ontology would be seen as a refinement to that theory?

The starting point for this research is to explore the concept of a foundational inquiry in physics. What does it mean for a particular research program to be foundational? What differentiates between those lines of inquiry which somehow get at the foundations of the theory, and those which are part of the normal progress of the theory? More importantly, assuming we can successfully answer that question, is there any way we can meaningfully compare differing approaches to the foundations of a theory?

I argue that QIT is information-theoretic by virtue of the fact that it characterizes quantum systems by their information–bearing properties, and they characterize interactions by their information–processing properties. However, I argue that the more fundamental feature is that it is a principle theory. QIT is not a metaphysical inquiry. The basic unit of analysis—the qubit—is taken as an unanalyzed primitive of the theory. The approach is more focused on describing possible macroscopic effects of the quantum world, and less concerned with using the theory as a guide to the underlying ontology of the world.

But then how is quantum information science a foundational inquiry? It is clear how the more metaphysically-oriented approach is a foundational inquiry—if we came to know that one of the proposed ontologies of quantum theory were true, then this would go a long way to solving the major outstanding conceptual puzzles of contemporary physics—it would solve the Measurement Problem, and it would likely show the way towards unifying quantum mechanics with relativity. With QIT, however, there is no such clear path to a dissolution of the puzzling aspects of quantum theory.

I will explore the hypothesis that a principle-theoretic conception of a physical theory must either presuppose some ontology, or be interpretable only instrumentally (and make no claim to describing the world as it is). To put it simply, the hypothesis states that there cannot be a physical theory, which is interpreted realistically, which only posits the existence of "rules". The "rules" must be about "stuff". Either the theory is presupposing the existence of some kind of "stuff" or another, or it cannot be interpreted realistically.

This is an outgrowth of the argument that appears in Chapter 6. PO is a general framework into which many of the ontic approaches to the foundations of quantum theory can be incorporated. Although PO and QITI share the common structure detailed in that chapter, they do differ on this fundamental feature. QITI denies the fundamentality of the search for an underlying ontology.

Relatedly, there are several questions to pursue surrounding recent results in the quantum information literature. Despite the fact that quantum information science usually shies away from discussions of metaphysics, Recent papers from two groups of collaborators have ignited a discussion of the ontic status of the wavefunction in the QIT community In the papers by Pusey, Barrett, and Rudolph [67], and Colbeck and Renner [68] [69], the related principles of No Signaling, Parameter Independence, and Free Choice play central roles. There are a variety of sets of principles assumed and derived in these papers. It will be one of my main goals in this chapter to clearly lay out and categorize the similarities and differences between each of these arguments. The subtle differences in assumptions made can have an important impact on the conclusions it is appropriate to draw from each of these papers.

Even though the Colbeck and Renner non-extendability argument relies primarily on the principle of Free Choice, I will present an argument that it is equivalent (with the addition of one assumption) to an argument against the possibility of extending quantum theory in a way that yields more information than is present in the quantum state, on pain of signaling. That is, the force of the no-go theorem relies on the assumption that No Signaling is true. The considerations from Chapters 2 and 3 related to the interplay between relativity and No Signaling, and the quantum information–theoretic motivations for ruling out signaling, are relevant here. These results are further examples that certain metaphysical principles are tacitly assumed at times in the quantum information debate. If this is the case, it may have bearing on my claim that metaphysics is more fundamental than the principles of quantum information theory.

## 7.3 Conclusion

The arguments of the papers collected in this dissertation have a fairly narrow scope. The focus has been on the peculiarities of the D-CTC model and surrounding issues. My claim is that Deutsch's analysis of the behavior of quantum systems in the presence of a CTC relies both on assumptions from QIT, and on assumptions from the ontic approaches to the foundations of quantum theory. In disentangling these threads, Deutsch's model threatens to unravel.

The broader project, however, is just beginning. The quantum information approach is fascinating and productive, but its promise as a solution to the fundamental issues at the heart of quantum theory is unproven. A systematic framework in which the QIT can be held up against the ontic foundational inquiries is a necessary step on the way to truly understanding not just what the theory tells us, but the world it attempts to describe.

# Bibliography

[1] David Deutsch. Quantum mechanics near closed timelike lines. *Physical Review D*, 44(10):3197–3217, November 1991.

[2] Kip S. Thorne. *Black Holes & Time Warps*. W. W. Norton & Company, New York, New York, 1994.

[3] Palle Yourgrau. *Gödel Meets Einstein: Time Travel in the Gödel Universe*. Open Court, Chicago, Illinois, 1999.

[4] J. Richard Gott. Closed timelike curves produced by pairs of moving cosmic strings: Exact solutions. *Physical Review Letters*, 66(9):1126–1129, 1991.

[5] J. Richard Gott. *Time Travel in Einstein's Universe*. Houghton Mifflin Company, New York, NY, 2001.

[6] Paul Davies. *How to Build a Time Machine*. Penguin Books, New York, New York, paperback edition, 2003.

[7] Stephen W Hawking. Chronology protection conjecture. *Physical Review D*, 46(2):603, 1992.

[8] David Deutsch. Quantum theory, the Church–Turing principle and the universal quantum computer. *Proceedings of the Royal Society of London A*, 400(97), 1985.

[9] Seth Lloyd. Quantum information science. 2009. Online Preprint. Retrieved from http://web.mit.edu/2.111/www/notes09/spring.pdf.

[10] David Deutsch. The structure of the multiverse. In *Proceedings of the Royal Society of London A*, volume 458, pages 2911–23, 2002.

[11] David Deutsch. *The Fabric of Reality*. Penguin Books, New York, New York, paperback edition, 1998.

[12] N. David Mermin. *Quantum Computer Science*. Cambridge University Press, Cambridge, UK, 2007.

[13] T.C. Ralph. Problems with modeling closed timelike curves with post-selected teleportation. 2011. arXiv: 1107.4675v1 [quant-ph].

[14] Timothy C. Ralph and Casey R. Myers. Information flow of quantum states interacting with closed timelike curves. *arXiv preprint arXiv:1003.1987v2*, 2010.

[15] Timothy C. Ralph, Gerard J. Milburn, and Tony G. Downes. Quntum connectivity of space-time and gravitationally induced de-correlation of entanglement. *Physical Review A*, 79, 2009.

[16] Seth Lloyd, Lorenzo Maccone, Raul Garcia-Patron, Vittorio Giovannetti, and Yutaka Shikano. The quantum mechanics of time travel through post-selected teleportation. 2010. arXiv:1007.2615v2 [quant-ph].

[17] Seth Lloyd, Lorenzo Maccone, Raul Garcia-Patron, Vittorio Giovannetti, Yutaka Shikano, Stefano Pirandola, Lee A. Rozema, Ardavan Darabi, Yasaman Soudagar, Lynden K. Shalm, and Aephraim M. Steinberg. Closed timelike curves via post-selection: Theory and experimental demonstration. 2010. arXiv:1005.2219v1 [quant-ph].

[18] Todd A. Brun, Jim Harrington, and Mark M. Wilde. Localized closed timelike curves can perfectly distinguish quantum states. *Physical Review Letters*, 102(210402), 2009.

[19] David Lewis. The paradoxes of time travel. *American Philosophical Quarterly*, 13(2):145–152, 1976.

[20] Igor Novikov. Can we change the past? In *The Future of Spacetime*, pages 57–86. Norton, New York, NY, 2002.

[21] Nicolas Gisin. Quantum correlations in Newtonian space and time: Arbitrarily fast communication or nonlocality. *arXiv preprint arXiv:1210.7308v1*, 2012.

[22] Christopher Timpson. *Quantum Information Theory and the Foundations of Quantum Mechanics*. Oxford University Press, Oxford, UK, 2013.

[23] Michael A. Nielsen and Isaac L. Chuang. *Quantum Computation and Quantum Information*. Cambridge University Press, Cambridge, UK, 2000.

[24] Tim Maudlin. Bell's inequality, information transmission, and prisim models. *PSA: The Proceedings of the Biennial Meeting of the Philosophy of Science Association*, Volume 1: Contributed Papers:404–417, 1992.

[25] Gilles Brassard, Richard Cleve, and Alain Tapp. Cost of exactly simulating quantum entanglement with classical communication. *Physical Review Letters*, 83(9):1874–1877, 1999.

[26] Michael Steiner. Towards quantifying non-local information transfer: Finite-bit non-locality. *Physics Letters A*, 270:239–244, 2000.

[27] Nicolas J. Serf, Nicolas Gisin, and Serge Massar. Classical teleportation of a quantum bit. *Physical Review Letters*, 84(11):2521–2524, 2000.

[28] Ben Toner and Dave Bacon. Communication cost of simulating bell correlations. *Physical Review Letters*, 91(18):1–4, 2003.

[29] Eric G. Cavalcanti, Nicolas C. Menicucci, and Jacques L. Pienaar. The preparation problem in nonlinear extensions of quantum theory. 2012. arXiv:1206.2725v1.

[30] John D. Norton. *Einstein for Everyone*. Nullarbor Press, Online, 2013.

[31] Jeffrey Bub and Itamar Pitowsky. Two dogmas about quantum mechanics. In Simon Saunders, Jonathan Barrett, Adrian Kent, and David Wallace, editors, *Many Worlds? Everett, Quantum Theory, and Reality*, chapter 14, pages 433–459. Oxford University Press, Oxford, UK, 2010.

[32] Albert Einstein, Boris Podolsky, and Nathan Rosen. Can quantum-mechanical description of physical reality be considered complete? *Physical Review*, 47:777–780, 1935.

[33] Don Howard. Einstein on locality and separability. *Studies in History and Philosophy of Science A*, 16(3):171–201, 1985.

[34] Tim Maudlin. *Quantum Non-Locality and Relativity*. Wiley-Blackwell, Chichester, UK, 3rd edition edition, 2011.

[35] Alain Aspect, Philippe Grangier, and Gérard Roger. Experimental tests of realistic local theories via Bell's theorem. *Physical Review Letters*, 47(7):460–463, 1981.

[36] Alain Aspect, Jean Dalibard, and Gérard Roger. Experimental test of Bell's inequalities using time–varying analyzers. *Physical Review Letters*, 49(25):1804–1807, 1982.

[37] Nicolas Gisin, Valerio Scarani, Wolfgang Tittel, and Hugo Zbinden. Optical tests of quantum nonlocality: from EPR–Bell tests towards experiments with moving observers. In *Proceedings, Annal. Phys.*, volume 9, pages 831–842, 2000.

[38] André Stefanov, Hugo Zbinden, and Nicolas Gisin. Quantum correlations with spacelike separated beam splitters in motion: Experimental test of multisimultaneity. *Physical Review Letters*, 88(12):120404, 2002.

[39] Valerio Scarani, Wolfgang Tittel, Hugo Zbinden, and Nicolas Gisin. The speed of quantum information and the preferred frame: analysis of experimental data. *Physical Letters A*, 276(1):1–7, 2000.

[40] Daniel Start, Augustin Baas, Cyril Branciard, Nicolas Gisin, and Hugo Zbinden. Testing the speed of 'spooky action at a distance'. *Nature*, 454(7206):861–864, 2008.

[41] Jeffrey Bub and Allen Stairs. Quantum interactions with cloed timelike curves and superluminal signaling. *Physical Review A*, 89(2), 2014.

[42] Nicolas Gisin. Weinberg's non-linear quantum mechanics and supraluminal communications. *Physics Letters A*, 143(1.2):1–2, January 1990.

[43] David Deutsch and Michael Lockwood. The quantum physics of time travel. *Scientific American*, pages 50–56, March 1994.

[44] Jonathan Barrett. Information processing in generalized probabilistic theories. *Physical Review A*, 75(3):032304, 2007.

[45] Marcin Pawłowski, Tomasz Paterek, Dagomir Kaszlikowski, Valerio Scarani, Andreas Winter, and Marek Żukowski. Information causality as a physical principle. *Nature*, 461(7267):1101–1104, 2009.

[46] Martin Ringbauer, Matthew A. Broome, Casey R. Myers, Andrew G. White, and Timothy C. Ralph. Experimental simulation of closed timelike curves. *Nature Communications*, 5(4145):1–7, June 2014.

[47] David Deutsch. Apart from universes. In Simon Saunders, Jonathan Barrett, Adrian Kent, and David Wallace, editors, *Many Worlds? Everett, Quantum Theory, and Reality*, pages 542–552. Oxford University Press, Oxford, UK, 2010.

[48] Transcript: Not (only) many worlds. In Simon Saunders, Jonathan Barrett, Adrian Kent, and David Wallace, editors, *Many Worlds? Everett, Quantum Theory, and Reality*, pages 597–607. Oxford University Press, Oxford, UK, 2010.

[49] David Wallace. *The Emergent Multiverse*. Oxford University Press, Oxford, UK, 2012.

[50] Detlef Dürr, Sheldon Goldstein, and Nino Zanghì. Quantum equilibrium and the origin of absolute uncertainty. *Journal of Statistical Physics*, 67:843–907, 1992.

[51] Sheldon Goldstein. Quantum theory without observers. *Physics Today*, Part One: March, pp. 42–46; Part Two: April, pp. 38–42 1998.

[52] Valia Allori, Sheldon Goldstein, Roderich Tumulka, and Nino Zanghì. On the common structure of Bohmian Mechanics and the Ghirardi-Rimini-Weber theory. *British Journal for the Philosophy of Science*, 59:353–389, 2008.

[53] Valia Allori, Sheldon Goldstein, Roderich Tumulka, and Nino Zanghì. Predictions and primitive ontology in quantum foundations: A study of examples. *British Journal for the Philosophy of Science*, 65(2):323–352, 2014.

[54] Valia Allori. On the metaphysics of quantum mechanics. In Soazig Le Bihan, editor, *Precis de la Philosophie de la Physique: d'aujourd'hui à demain*. Vuibert, 2013.

[55] Valia Allori. Primitive ontology and the structure of fundamental physical theories. In Alyssa Ney and David Z. Albert, editors, *The Wave Function*. Oxford University Press, Oxford, UK, 2013.

[56] Johannes Kofler and Anton Zeilinger. The information interpretation of quantum mechanics and the Schrödinger cat paradox. *Sciences et Avenir Hors-Série*, (148), 2006.

[57] Christopher Fuchs. Quantum mechanics as quantum information (and only a little more). 2002. arXiv preprint: quant-ph/0205039.

[58] Rob Clifton, Jeffrey Bub, and Hans Halvorson. Characterizing quantum theory in terms of information-theoretic constriants. *Foundations of Physics*, 33(11):1561–91, 2003.

[59] Jeffrey Bub. Why the quantum? *Studies in the History and Philosophy of Modern Physics*, 35:241–266, 2004.

[60] Jeffrey Bub. Quantum mechanics is about quantum information. *Foundations of Physics*, 35(4):541–560, 2005.

[61] Itamar Pitowsky. Quantum mechanics as a theory of probability. In William Demopoulos and Itamar Pitowsky, editors, *Physical Theory and Its Interpretation*, The Western Ontario Series in Philosophy of Science, pages 213–240. Springer, 2006.

[62] John S. Bell. The theory of local beables. In *Speakable and Unspeakable in Quantum Mechanics*. Cambridge University Press, Cambridge, UK, 1987.

[63] John S. Bell. Beables for quantum field theory. In *Speakable and Unspeakable in Quantum Mechanics*. Cambridge University Press, Cambridge, UK, 1987.

[64] Bradley Monton. Wave function ontology. *Synthese*, 130:265–77, 2002.

[65] Bradley Monton. Against 3n-dimensional space. In Alyssa Ney and David Z. Albert, editors, *The Wave Function*, pages 154–167. Oxford University Press, 2013.

[66] David Wallace. *The Emergent Multiverse: Quantum Theory According to the Everett Interpretation*. Oxford University Press, Oxford, UK, 2012.

[67] Mathew Pusey, Jonathan Barrett, and Terry Rudolph. The quantum state cannot be interpreted statistically. arXiv: 1111.3328v1 [quant-ph], November 2011.

[68] Roger Colbeck and Renato Renner. No extension of quantum theory can have improved predictive power. *Nature Communications*, 2(411):1–5, August 2011.

[69] Roger Colbeck and Renato Renner. Is a system's wave function in one-to-one correspondence with its elementds of reality? *Physical Review Letters*, 108:150402–1–150502–4, April 2012.