The Physical Basis of Quantum Relativity

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15^{th} UK and European Meeting on the Foundations of Physics
29-31 March 2007, University of Leeds, UK

April 2, 2007

Abstract

Standard Quantum mechanics (SQM) deals with observers, frames of reference (apparatus) and systems under observation (SUOs). Heisenberg based his approach to quantum mechanics on a desire to avoid metaphysical (i.e. unobservable) concepts, dealing only in terms of experimentally observable quantities. Following this idea, we describe an approach to quantum mechanics which deals only with labstates, which represent the observer's quantum information about the apparatus. This approach is compatible and consistent with Hume's philosophy known as empiricism. We show that conventional ideas do not work without modification when we consider certain quantum experiments involving classical special relativistic transformations. We discuss the appearance of *quantum horizons*, which present a barrier to information transmission between initial and final state apparatus whenever these are in relative motion.

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1 Introduction

In general, physicists try to discover the laws of the universe via experiments on *systems under observation* (SUOs), or so they believe. Undoubtedly, this is a good interpretation of what they are doing in the laboratory as far as classical physics is concerned, but what about quantum physics?

We can do no better than read what some of the great quantum theoreticians thought about this issue. In his seminal 1927 paper on the uncertainty principle, Heisenberg wrote [1]

> *"I believe that one can fruitfully formulate the origin of the classical 'orbit' in this way: the 'orbit' comes into being only when we observe it."*

Rather independently, and quite a few years later, the young Richard Feynman wrote in his Doctoral thesis [2]

> *"... and all of the apparent quantum properties of light and the existence of photons may be nothing more than the result of matter interacting with matter directly, and according to quantum mechanical laws."*

It does not seem to me that these scientists were saying things precisely in accordance with the first sentence of this article. It seems to me that they are saying things flatly in contradiction to it. We should be worried by the implications of what they wrote, regardless of whether we are philosophers of science or hard-boiled mathematical physicists. If what Heisenberg and Feynman wrote has even a touch of validity, what price then the classical world view of objects "existing" in space, waiting for their properties to be discovered by observers?

Now a famous result in standard quantum mechanics (SQM) consistent with this line of concern is the Kochen-Specker theorem [3] and its derivatives, which in effect says that a state of an SUO does not "have" already existing incompatible classical values such as position and momentum waiting to be discovered by observers. This supports the notion that classical states and quantum states of SUOs are rather different concepts. It seems to me, however, that what Heisenberg and Feynman said goes much deeper than that. They seem to be questioning the very existence of SUOs. Take Heisenberg's comment. It is very difficult to imagine an electron existing without a trajectory, so if the trajectory does not exist when no-one is looking, does that not imply that the electron does not exist as well when no-one is looking? As for Feynman's statement, it certainly throws the photon-as-particle concept right out of the laboratory window. If anyone doubts the issues of the photon-as-particle concept, they could do no better than read Harry Paul's book on quantum optics [4], where he discusses many experiments where it is clear the photon-as-particle concept is wrong.

My programme of research has followed a line of thought consistent with Heisenberg and Feynman's comments and developed a quantum mechanics (QM) formalism

I call Quantized Detector Networks, in which the SUO concept is deliberately neglected [5, 6, 7]. Philosophers may find this reminiscent of the branch of philosophy known as empiricism, developed by David Hume [8] and others, which is based on the principle that sensory experience is the sole source of knowledge[1]. It is surely irrefutable that the only thing experimentalists can ever deal with is their laboratory apparatus. Experimentalists push buttons, look at screens, and count signals. Everything else is inferred, i.e., imagined in terms of some preconditioned theory or set of concepts in the mind of the theorist.

There is no space here to discuss further the motivation for my system-free approach to quantum mechanics, except to make the following brief comments. First, there are several factors operating together which contrive to create the illusion that SUOs exist: *i*) the classical world view of SUOs is very good most of the time; *ii*) we need advanced technology to detect quantum phenomena; *iii*) we are generally swamped by vast numbers of degrees of freedom which hide subtle quantum departures from the classical world view and *iv*) patterns of matter tend to persist long enough to justify us objectifying them. The reality however is that all our objectifications such as electrons, tables, hurricanes and people, are better thought of as *processes highly dependent on the context in which they are discussed.* Functionality has a lot to do with it. A table is just a collection of molecules from some points of view, and a place to spill coffee over from other points of view. Cut off a leg and the table can still function as a table, provided it does not topple over.

In this article, I shall apply my view of SUO's to special relativity (SR) in a rather straightforward way. Basically, I shall ask the question "*how is the experiment actually performed?*", rather than the more traditional question "*how do different observers describe that SUO?*"

2 Galilean & Lorentz Transformations

In the following, I shall restrict the discussion to a one time, one space dimensional spacetime and deal with two relatively moving inertial frames $\mathcal{F}$ and $\mathcal{F}'$. I have to use the language and concepts of conventional SR, but my programme of research intends in the long run to replace these with others more consistent with my scientific philosophy.

For a given event P in spacetime, write

$$P \sim (t_P, x_P) \sim [t'_P, x'_P,], \tag{1}$$

where (t_P, x_P) denotes the coordinates of P as given by $\mathcal{F}$ and $[t'_P, x'_P,]$ denotes the coordinates of P as given by $\mathcal{F}'$. Now for Newtonian spacetime, a typical Galilean

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[1] It occurs to us that Decartes' famous dictum "I think therefore I am" may be interpreted in terms of what Heisenberg said about electron trajectories. We could perhaps rewrite Decartes' words in the form "I have observed myself thinking, therefore I exist."

transformation takes the form

$$\boxed{\begin{array}{l} t' = t \\ x' = x - vt \end{array}}, \tag{2}$$

whereas for Minkowski spacetime, we would be using the Lorentz transformation

$$\boxed{\begin{array}{l} t' = \gamma\left(v\right)\left\{t - vx/c^2\right\} \\ x' = \gamma\left(v\right)\left\{x - vt\right\} \end{array}}, \tag{3}$$

where

$$\gamma\left(v\right) \equiv \frac{1}{\sqrt{1 - v^2/c^2}}. \tag{4}$$

I (the author of this article) think I understand Galilean transformations, but quite frankly, I am a bit worried about the Lorentz transformation. Of course I "know" what it means conventionally, having studied mathematical physics for a long time, but I think it goes deeper than the conventional glib view of it as just a coordinate transformation. I have come to the conclusion that I don't quite understand (i.e., believe) the conventional wisdom. It's too naive. With respect, people tend to be a bit careless. The Lorentz transformation comes from a classical view of the world where objects "exist" and can be looked at and their properties determined by observers **without any cost to the imagined SUO**.

To illustrate my worries, consider the conventional relativistic quantum mechanics of a relativistic particle of rest mass m. A typical approach would be to postulate that the wave-function of the particle (what a loaded phrase) is a Lorentz scalar, so we would write

$$\varphi\left(t, x\right) = \varphi'(t', x') \tag{5}$$

over all points of spacetime where the description was valid. Specializing this to a plane wave gives

$$\boxed{\varphi(t, x) \simeq e^{i(E't' - p'x')/\hbar} = e^{i(Et - px)/\hbar} \simeq \varphi'(t', x')}, \tag{6}$$

and from this we deduce the relationship between what each frame says about the particle's energy E and momentum p :

$$\boxed{\begin{array}{l} E' = \gamma\left(v\right)\left\{E - vp\right\} \\ p' = \gamma\left(v\right)\left\{p - Ev/c^2\right\} \end{array}}. \tag{7}$$

But I think Quantum Mechanics should say something different (or at least, put things differently). We should move away from naive "Lorentz Covariance" arguments, which are fine for a classical world view, but problematic in a quantum context.

Recall Heisenberg's Uncertainty Principle [1]. It tells us that we cannot simultaneously "know" the position x and momentum p of a particle. There are several ways to "explain" this. An "Old View" argument is to note that we actually cannot perform incompatible experiments on an SUO at the same time. For example, Heisenberg argued that if we tried to determine the position of an electron which was at rest using light, we would inevitable need to interact with the electron. That interaction (i.e., the process of observation) would necessarily impart momentum, so we could no longer be sure of the electron's state of rest. A more "Modern View" would be to say that particle states do not "have" incompatible values simultaneously, which is consistent with the Kochen-Specker theorem mentioned above [3].

In the "system-free" approach, we cannot consistently use the "Modern View" in its standard form[2] because we don't have SUO's. Fortunately when it comes to SR and quantum experiments, the "Old View" argument is rather good, because it is an empirical fact that we cannot measure a single particle's momentum in two frames simultaneously **in a given run**. Please be very careful to understand precisely what is meant by this. Take two inertial frames of reference $\mathcal{F}$ and $\mathcal{F}'$. Place a photon detector in each. If the detector D in $\mathcal{F}$ gives a click conventionally signifying that a photon has been observed, the detector D' in $\mathcal{F}'$ cannot also give a click **for that photon**. Only one click per photon is allowed.

This means that it is technically wrong to use phrases such as "if an observer in frame $\mathcal{F}$ sees a photon with frequency ν then an observer in frame $\mathcal{F}'$ would see that photon with a Doppler shifted frequency ν'. Of course, when pressed about this, conventional minded theorists would begin to talk about ensembles of photons all prepared identically, with non-intersecting subsets being observed by D and D' respectively. But that simply proves our point, which is that much more care is needed in using conventional language to describe quantum processes. The same criticism can be levelled at ideas such as "general covariance". Such language is good for classical mechanics, but looks misleading in a quantum processes framework. Surprisingly, it looks like a lot of philosophers of science don't pick up or understand this point. It may be they are swayed by the widespread use of such language in the scientific community. That scientists talk like that is excusable, given most scientists are pragmatists and don't see that these issues as relevant. It should be the philosophers who are asking scientists to clarify more completely just what they mean by such terminology, particularly in terms of quantum observation.

This brings us to an important and on-going debate/conflict between the Bayesian view of probability and the Frequentist view. I think that a dynamical theory of physical reality should be described via Bayesian contextuality, not via frequentist probabilities. I would summarize this by the motto

The Gambler's view of the future
not
The Accountant's view of the past.

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[2] Actually, I should be able to incorporate it into my discussion of the *labstates*, which are the quantum states of the apparatus.

A more familiar way of putting this would be

Process time
not
Manifold **time (the Block universe).**

Of course, this has serious ramifications for relativity, because there is a fundamental issue: SR singles out no particular frame of reference as special, whereas observers define special frames of reference. If we are going to focus on observers and apparatus and not SUOs embedded in spacetime, then we will have to worry about this issue. Essentially,

we will have to take much more care in the description of experiments.

3 Inter-frame physics

Let's get down to specifics. Conventionally, physicists like to describe experiments in one inertial frame. Only then do they consider transforming to some other frame. Equivalently, physicists do not like to use different inertial frames in the same experiment. Typically, they would describe an initial quantum state and possible final states defined over hyperplanes of simultaneity in **the same frame**, such as $\mathcal{F}$, as shown in Figure 1.

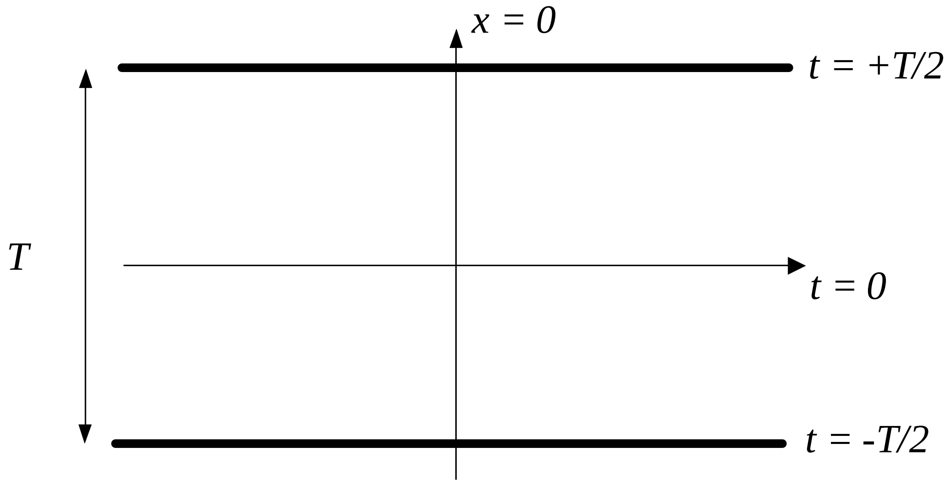

Figure 1. *Initial and final states in High Energy Particle Physics descriptions of scattering processes tend to be defined in hyperplanes of simutaneity in the remote past and future respectively and in the same inertial frame of reference.*

We are not restricted to hyperplanes. Schwinger showed it was possible to discuss quantum field theory in terms of more general non-intersecting spacelike hypersurfaces, as in Figure 2.

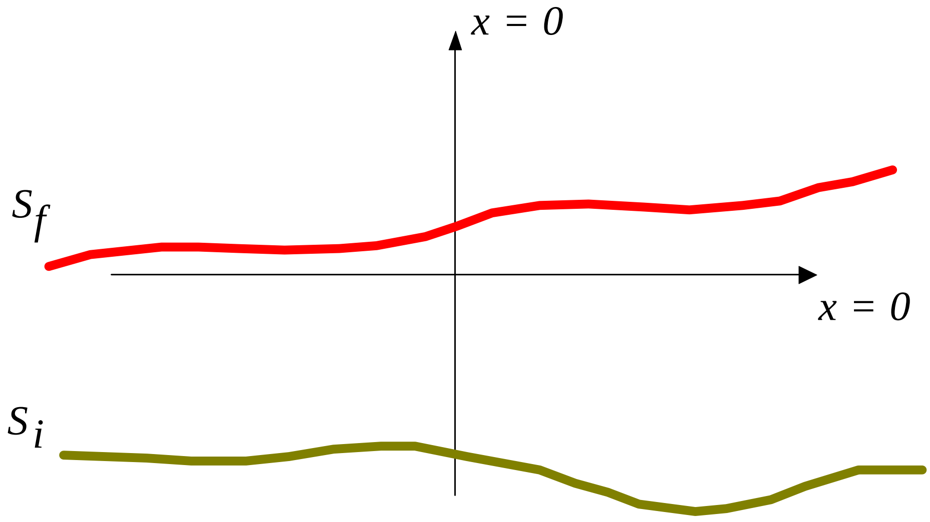

Figure 2. *Schwinger showed it was possible to replace the hyperplanes of simultaneity by more general, non-intersecting spacelike hypersurfaces. In General Relativity, an analogous approach is to use foliations of the spacetime manifold (if possible).*

That's perfectly fine but not the most general discussion we could have. What about genuine inter-frame experiments, such as the following: consider an initial state prepared in inertial frame $\mathcal{F}$ and a final state observation in some relatively moving inertial frame $\mathcal{F}'$. There's nothing in physics to stop us doing this. Or is there?

I can't see any problems with the Galilean transformations, because Galilean hyperplanes of simultaneity coincide between all (Galilean) inertial frames. The problem I have arises with relativistic finite-time inter-frame experiments. Consider an initial state prepared in frame $\mathcal{F}$ at time $t = 0$ and final state outcomes detected in frame $\mathcal{F}'$ at finite time $t' = T' > 0$, shown in Figure 3.

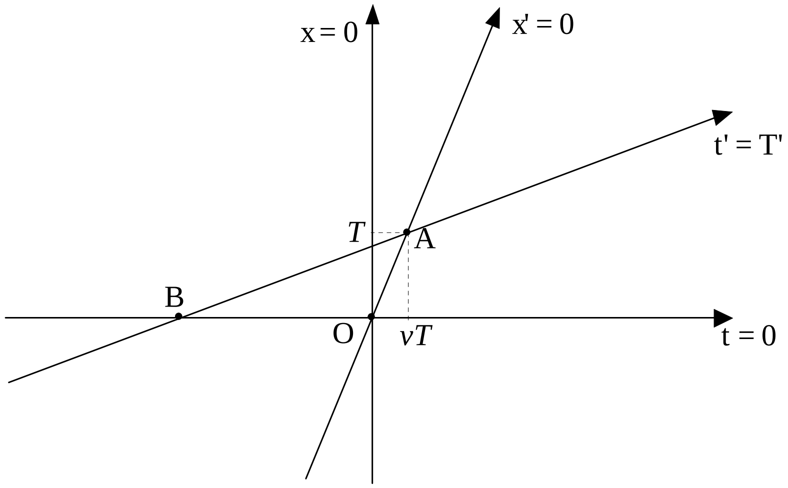

Figure 3. *Inertial frames F and F' have a common origin of coordinates at O. An inital state is prepared on the hypersurface $t = 0$ (according to F) and outcomes are detected on the hypersurface $t' = T'$ (according to F').*

The problem we run into is that hyperplanes of simultaneity in $\mathcal{F}$ and $\mathcal{F}'$ intersect. In Figure 3 the hyperplanes of simultaneity $t = 0$ and $t' = T'$ intersect at event B. Suppose $\mathcal{F}$ prepares a quantum state at time $t = 0$ involving events P, Q. What can $\mathcal{F}'$ say at time $t' = T' > 0$?

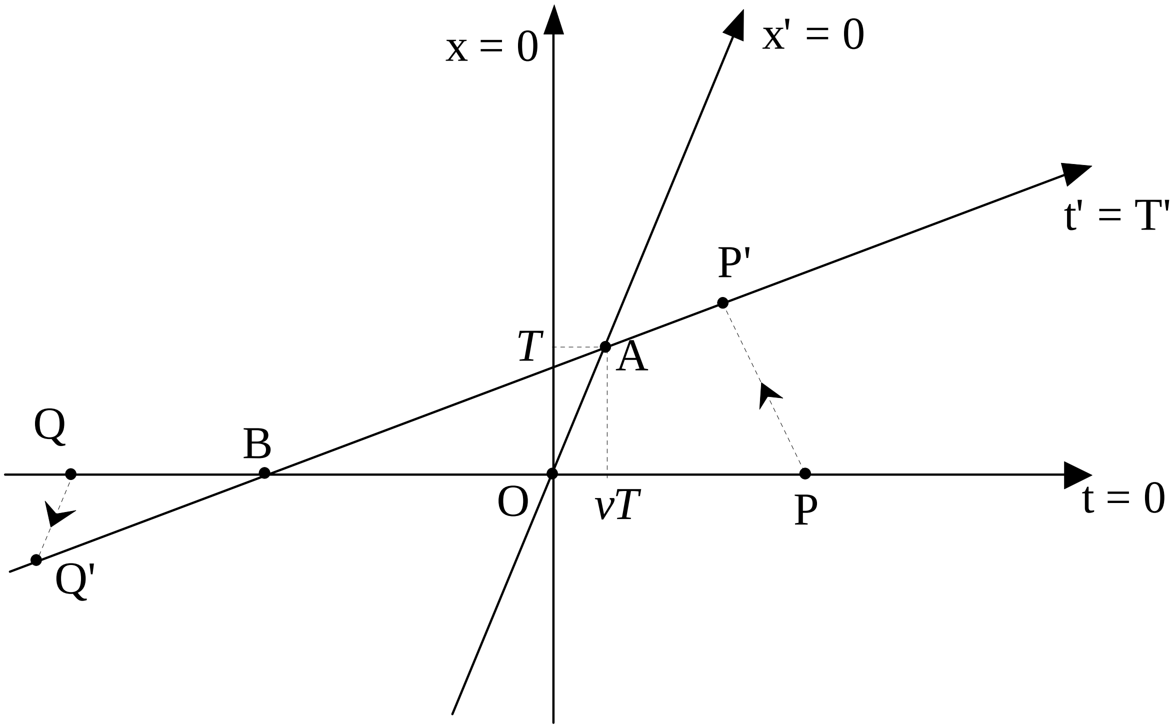

Figure 4. *Quantum and classical causality allows physical signals to propagate from P to P', but not Q to Q'.*

Certainly, in both classical and quantum physics, detectors at P' can receive a signal from P, as shown in Figure 4. Indeed, any set of events on the hyperplane $t' = T'$ inside the forwards lightcone with vertex at P can receive a physical signal from P. But a detector at Q' cannot receive a signal from Q. **It would not be correct to say there is an antiparticle going from Q to Q'** (i.e., backwards in time, as in the Feynman-Stueckelberg idea), as a means of circumventing this issue. There are several reasons for this, two of which are

1. the apparatus at Q can be made identical to that at P, with both only capable of emitting signals and not capable of absorbing signals;
2. we would have a quantum outcome at Q' before state preparation at Q, contrary to quantum principles.

We conclude that event B is a critical barrier to communication between hyperplane $t = 0$ in $\mathcal{F}$ and hyperplane. For want of a better term, we shall call this a *quantum horizon* (with apologies if this means something else to some people).

4 Quantum horizons

A quantum horizon depends on frames of reference **and** choice of hyperplanes of simultaneity. It is therefore completely tied up with state preparation and outcome detection. Changing any parameters associated with these processes changes the position of the quantum horizon. It is instructive to determine the coordinates of B. We find

$$\boxed{B \sim (0, -\frac{c^2 T'}{\gamma(v) v}) \sim [T', -\frac{c^2 T'}{v}]} \tag{8}$$

using our convention. To understand this, recall a basic fact about **de Broglie waves.** In de Broglie's view, a physical particle moving with speed $v < c$ has associated with it a de Broglie wave moving with speed $w_v > c$, such that

$$\boxed{w_v = \frac{c^2}{v}}. \tag{9}$$

Note that because $v < 0$ then $w_v > c$. So we can write

$$\boxed{B \sim [T', -w_v T']}. \tag{10}$$

The quantum horizon behaves as if it were the wavefront of a de Broglie wave setting out from the origin of coordinates in the direction taken by frame $\mathcal{F}$, as seen by observers in frame $\mathcal{F}'$. The quantum horizon disappears to infinity as T' gets larger, or v gets smaller, or if we take the limit $c^2 \to \infty$. The conventional picture shown in Figure 1 corresponds to $v = 0$, and then B has disappeared off to spatial infinity and there is no problem.

Actually, for finite-time genuine inter-frame experiments ($T' < \infty, v \neq 0$) we can always centre coordinates on a quantum horizon, and then the picture looks remarkably neat and symmetrical. The above experiment looks like Figure 5:

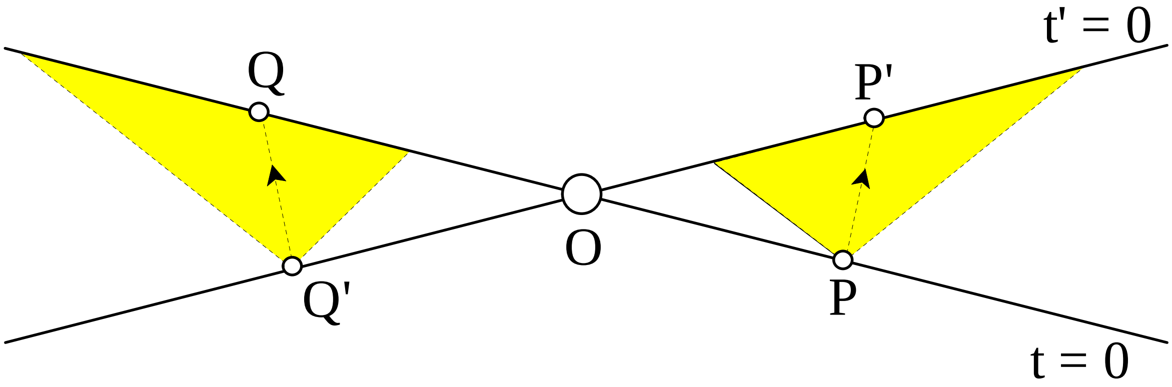

Figure 5. *Placing the origin of coordinates on the quantum horizon B shows the inherent symmetry between inertial frames. This is the basis of our "split-causality" proposal.*

We can see from this diagram that any antiparticle "explanation" of signals propagating from Q to Q' is ad hoc and asymmetric. The symmetry shows that we would expect signals to propagate from P' to P on that basis. Of course, this need not be an issue in a reversible deterministic classical universe (because time has no obvious direction), but it would be a fundamental issue for quantum mechanics and its probability interpretation. Figure 5 is the basis of our proposal for a "split-causality" test of the relativity principle [9]. This is **not a trivial test of the relativity principle.**

5 Heisenberg nets

Because our approach focuses on signals from apparatus, then the inter-frame experiment discussed above requires us to take much more care with the Hilbert spaces we can use in our formalism. This can be addressed by abandoning the idea that all states evolve in a fixed Hilbert space. Now we define a separate Hilbert space for each relevant instant of the observer's time. By "relevant", we mean at those times where genuine information is being exchanged between the observer and their apparatus. This means state preparation and outcome detection, but **not** at other times. We can stretch Heisenberg's dictum about unobserved electron trajectories to concepts of space and time: *time and space have no existence outside of what an observer detects.* This accords with the fundamental idea that quantum mechanics is about information exchange between observer and apparatus.

As mention above, we have given a general formalism outlining these ideas called the Quantized Detector Network approach [7]. At a given instant of an observer's time, all the signal generators and signal detectors **at that time** form a *Heisenberg net.* Associated with each Heisenberg net is a distinct Hilbert space, which is the tensor product of all the qubits associated with those detectors. In principle it may be infinite dimensional; in practice it will be finite dimensional. Considering the above experiment, Figure 6 is relevant:

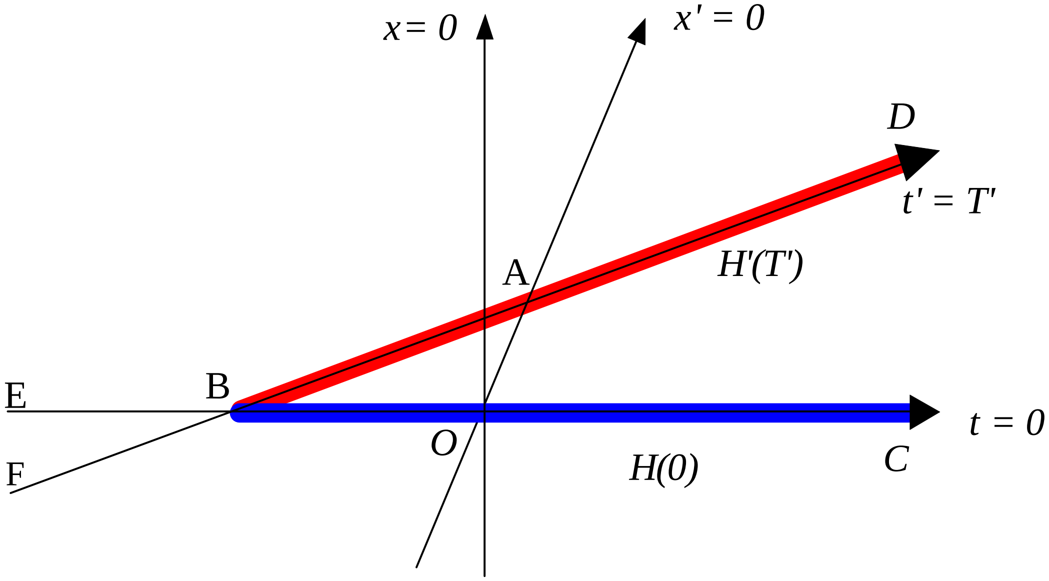

Figure 6. *An inter-frame experiment should be decribed in terms of mapping from initial Hilbert space* $H(0)$ *to final Hilbert space* $H'(T')$*. These Hilbert spaces need not have the same dimension, if the preparation and detection apparatus consists of finite numbers of signal detectors/generators.*

The relevant Hilbert space for the initial state involves signal generators situated at events on that part of the hyperplane $t = 0$ running from the quantum horizon B to C (essentially spatial infinity). The relevant Hilbert space for the outcome states involves signal detectors situated at events on the part of the hyperplane $t' = T'$ running from the quantum horizon B to D (essentially spatial infinity). Note these Hilbert spaces do not involve detectors everywhere on the x-axis or x'-axis. That's why I said I did not quite understand the Lorentz transformation (3), and why I just don't know precisely what people mean when they talk about "Lorentz covariance". I half suspect[3] they have not thought about these issues in this way.

6 Concluding remarks

By focusing on apparatus and signals from apparatus, rather than on SUO's, I have identified serious issues concerning finite-time inter-frame quantum experiments. When I read papers on say quantum gravity, I get worried, because no one seems to mention quantum horizons or issues to do with actual experiments. Symmetries, manifolds, metrics, transformations and suchlike are all discussed as if classical concepts were valid, without reference to apparatus and details of observation, even when quantum gravity is discussed. That seems wrong and inconsistent. I have come across remarkably few quantum theorists and philosophers who agree with my point

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[3] Actually, I am sure.

of view. That does not worry me, because I think it's encouragement enough to know Heisenberg and Feynman worried about these issues.

Of course, people would argue that they know what they were doing and that these things are all meant to be discussed in terms of counterfactuals. Take the question of symmetries in quantum mechanics. It's quite usual to talk about unitary transformations of states as if that was a normal thing in the real world. In practice, we cannot transform equipment when we build it. Just try to rotate the Geneva particle collider: it's not possible. It is a very important and generally understated principle in quantum mechanics that *if something did not happen*, **it does not count.** I like to call this *Peres' principle*, because I think Asher Peres was the first quantum theorist I read about to have put this notion in those terms. I imagine Bohr said the same thing but differently a long time ago. It's really exactly what Heisenberg said in the quote I gave at the beginning: if you have not looked at an electron trajectory, it does not exist/count. People have problems with that, because real life uses counterfactuality all the time, and it's very difficult not to employ it in discussions involving quantum processes.

I think there would be consequences if we were to take a system-free approach to gravitation. First of all, we would have to be much more careful in everything we say. Ideas such as general covariance, symmetries, unitary transformations *may* have a place, but without detailed examination of what they mean to the observer in the laboratory, I would avoid them at all costs. It should be kept in mind that special and general relativity were born from a classical world view of reality, before the advent of quantum mechanics proper in 1925. Quantum principles of the sort enunciated by Heisenberg and Born have not been found wanting. This suggests that "quantum gravity" should be reformulated through a proper quantum theory of observers and apparatus, and **not** via manifolds, SUOs and suchlike.

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