Causal Loops in Quantum Phenomena?

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Abstract. A common view has it that there is a tension between quantum phenomena and the special theory of relativity. Yet, an ongoing debate concerning the prospects of relativistic quantum theories persists. In this paper, I consider two recent arguments for the impossibility of certain relativistic quantum theories, due to Arntzenius (1994) and Maudlin (1994). The main idea of both arguments is that if these theories were possible, causal loops would also be. But, it is argued, the consistency conditions of such loops would exclude the very possibility of these theories. I argue that Arntzenius' and Maudlin's lines of reasoning fail because they rely on untenable assumptions about the nature of probabilities in causal loops.

1. **Introduction.** Granted plausible assumptions about the quantum realm, the curious quantum correlations between distant systems imply the existence of non−local influences that are difficult to reconcile with Relativity theory. Yet, the question of whether quantum phenomena are compatible with relativity is a matter of ongoing controversy, the resolution of which depends on the exact nature of quantum non−locality and the interpretation of Relativity.

Relativity is popularly conceived as excluding any non−local (i.e. faster than light) influences. Accordingly, it is sometimes maintained that only 'local quantum theories', i.e. theories that involve no non−local influences, can be reconciled with Relativity.

The prospects of local, quantum theories seem dim. But, in any case, the popular view that relativity excludes any type of non−locality, though intuitively compelling, is hard to defend (Maudlin 1994; 1996, Section 3). A more plausible view has it that Relativity excludes certain types of non−locality, but there is an ongoing controversy over their nature. Since different quantum theories postulate different non−local mechanisms for reproducing the quantum correlations, the question of the compatibility of quantum phenomena with Relativity is again a controversial matter (Maudlin 1994, 1996; Berkovitz 1998b, Section 3 and references therein).

In this paper, I focus on two recent attempts to demonstrate that certain types of local and non−local, relativistic quantum theories are impossible. The arguments have a structure of *reductio*: If these theories were possible, causal loops would also be. But, it is argued, the consistency conditions of such loops would exclude the very possibility of these theories.

I argue that both arguments rely on untenable assumptions about the nature of probabilities in causal loops.

The structure of the paper is as follows. In the next section, I review Bell's (1987) seminal argument for non−locality between distant events in Einstein−Podolosky−Rosen (EPR) experiments. Bell's argument relies on the assumption that the probability of states of particles at a certain time is independent of the measurements they (might) undergo at a later time. This assumption would be challenged if backwards causation were possible. Postulating a backwards−causation mechanism from measurement events to earlier particles' states, John Cramer suggested that a quantum theory could account for the correlations between distant events in EPR experiments by a local, common−cause mechanism (1980; 1986).

In Section 3, I consider Tim Maudlin's argument for the impossibility of Cramer's theory, as well as any other quantum theory that involves both forwards and backwards influences (1994, pp. 197−200). In Section 3.2, I argue that Maudlin's argument is in effect that if Cramer's theory were possible, certain causal loops would be. But, assuming that long−run (relative) frequencies of events should (almost certainly) equal their chance, such loops would be inconsistent.

The assumption of equality between chances and long−run frequencies is common in linear causation. But, as I argue in Section 4, it is untenable in causal loops.

In Section 5, I consider Arntzenius' argument for the impossibility of certain non−local, relativistic quantum theories, where the probability of nearby outcome depends on the 'setting' of the distant measurement apparatus to measure a certain quantity. It is widely believed that this type of non−locality, the so−called 'parameter dependence', is difficult to reconcile with Relativity. Yet, there are no conclusive arguments to this effect. In his 1994 (Section 3), Arntzenius suggested a general argument for the impossibility of any relativistic, 'parameter−dependent' theory. The main idea of this argument is that if such theories were possible, causal loops could easily be constructed by two causally related EPR experiments. But, argues Arntzenius, the consistency conditions of such loops require parameter *independence*.

In Section 5.2, I argue that similarly to Maudlin, in his argument Arntzenius implicitly made untenable assumptions about the nature of probabilities in causal loops.

2. Bell's argument for quantum non−locality in the EPR experiment

2.1. The EPR experiment. Recall the EPR experiment. Pairs of particles are emitted in opposite directions, L (left) and R (right). When the particles are far apart (i.e. space−like separated), each of them encounters a measurement apparatus, which can be set to measure one of two different physical quantities: L1 and L2 in the L−wing and R1 and

R2 in the R−wing. (The typical quantities are spin or polarization in different directions.) Measurement of these quantities can yield one of two opposite outcomes: either x or ¬x in the L−wing (e.g. spin 'up' and spin 'down' in the *z*−direction) and either y or ¬y in the R−wing.

According to orthodox quantum mechanics (QM) and (statistical analyses of) actual experimental results, the distant outcomes are correlated with each other. The nature of this correlation strongly suggests the existence of mysterious non−local connections between distant events. The question is then: are these non−local connections peculiar to QM, or are they fundamental characteristics of the quantum realm phenomena – characteristics that would be reflected in any other quantum theory?

2.2. Factorisable models of the EPR experiment. Assuming that QM is empirically adequate, any theory of the quantum realm will have to reproduce the QM statistics for EPR experiments. Accordingly, models of EPR experiments in such theories will have to satisfy certain constraints. Bell suggested the following general framework for analysing these constraints (Bell 1987, Chaps. 2, 4, 7 and 8; Berkovitz 1998a, Sections 2−3 and 1998b, Section 2).

A model of the EPR experiment postulates that for each particle pair, there is some physical state λ that together with the setting of the L− and the R−apparatus jointly prescribe probabilities for both: single and joint outcomes. The state λ is generally different from the QM wave−function of the particle pair, ψ. The idea is that λ is a more complete pair−state. Accordingly, pairs with the same ψ could have different states λ, which give rise to different probabilities of outcomes for the same type of measurements.

The model also postulates for each ψ a probability distribution over the different possible λ−states. It is assumed that this distribution is independent of the settings, henceforth, 'λ −independence'.

Although the probabilities of outcomes in states λ generally deviate from the probabilities prescribed by ψ, the model recovers the QM statistics by averaging over the model probabilities according to the distribution of the λ, henceforth 'QM−predictability'.

It is commonly assumed that in local models of EPR experiments, the probability of joint distant outcomes would factorise into the product of the probabilities of single outcomes, henceforth 'factorisability'. The idea is that in such models, the probability of a nearby outcome would be independent of the distant outcome and setting.

2.3. Bell's theorem. Bell's theorem asserts that any model of the EPR experiment that satisfies λ−independence, QM−predictability and factorisability is committed to so−called 'Bell inequalities', which are violated by QM and (statistical analyses of) actual experiments (Bell 1987, Chapters 2, 4 and 7; Redhead 1987, Section 4.3). Since actual experiments provide an overwhelming support for the QM predictions (Redhead 1987, Section 4.3), a consensus has it that QM−predictability must hold and that (due to the violation of Bell inequalities) this condition cannot jointly obtain with λ−independence and factorisability. So either factorisability or λ−independence must fail.

3. On the impossibility of local, backwards−causation quantum theories

3.1. Maudlin's argument. λ−independence is a very plausible assumption. Yet, it would fail if measurement events influenced the pair's state at the (earlier) emission time. Cramer's 'transactional' interpretation of quantum mechanics postulates such causal mechanism (1980; 1986).

In this theory, the source in EPR experiments not only emits a particle pair with a wave function that propagates forward in time to the measurement devices; each of the measurement devices also sends a wave backward in time to the source. So quantum events are determined by the interaction of wave functions that propagate both forward and backward in time. Accordingly, λ−independence fails – the setting of measurement devices influences pair's state at the emission time – and so Cramer's theory reproduces the quantum correlations between distant events without any non−locality.

Producing a consistent quantum theory that incorporates both forwards and backwards causation is a rather tricky business, particularly in indeterministic theories such as Cramer's. But, argues Maudlin, things are even worse since this theory and any similar backwards−causation theory are inconsistent (1994, pp. 197−200).

Before turning to this argument, let us first briefly review how Cramer's theory works. Consider a beta−decay experiment. At the emission time, the source is unshielded, allowing a beta particle to escape either to the right or to the left, where absorbers are set up to measure the particle's polarization in a certain direction. In Cramer's theory, the atom sends an "offer" wave forward in time to the absorbers. The wave is the standard, non−collapsed wave function. Both absorbers receive this offer wave sometime later and each of them sends backward in time a "confirmation" wave, which is the time−reverse of the offer it received. The two confirmation waves arrive at the emitter providing it with a choice to complete the "transaction" either by sending the beta particle to the left− or to the right−absorber. The chance that either absorber will be chosen is proportional to the strength of the confirmation wave received from it.

The transactional theory has certain particular problems (Maudlin …). But, argues Maudlin, there is a general problem that will arise for any stochastic theory of the same sort: any such theory would be inconsistent.

To sustain this claim, Maudlin invites us to consider the following version of a beta−decay experiment. At t_0 a radioactive source is unshielded, allowing a beta particle to escape either to the right or to the left. Absorber A is situated 1 meter to the right. Initially, absorber B is situated 2 meters to the right, but it is built on pivots so it can be swung around to the left very quickly on command (for more details, see Maudlin 1994, p. 200). If the particle is emitted to the right, it will be absorbed by A at t_1, a second later than t_0. If the particle is emitted to the left, absorber A will fail to absorb it at t_1 and accordingly absorber B will be swung quickly to the left and absorb the particle at t_2, 2 seconds after the emission.

It would be easy to set the experiment so that each of these two results would have 50% chance. Now, when absorber B is swung to the left, there will be two confirmation waves sent back from the future; one from absorber A in the right wing and one from absorber B in the left wing. The waves will have equal amplitudes as to dictate equiprobability of the two possible outcomes. Yet, the particle will always be detected by absorber B. So every time the emitter receives a confirmation wave from absorber B, the particle will go to this absorber even though the magnitude of the confirmation wave from this absorber determines chance ½ for such outcome. Accordingly, the long−run (relative) frequency of B−absorption, 1, will deviate from its chance, ½, in contradiction to the common assumption that in the long run frequencies of events (almost certainly) equal their chance.

3.2. Causal loops in Cramer’s transactional theory. Maudlin’s thought experiment involves a causal loop. And his argument is basically that in such loop, the long−run frequency of B−absorption will (almost certainly) deviate from its chance.

The reasoning is as follows. When the beta particle is emitted to the left, absorber A in the right wing fails to absorb the particle at t_1 (event $\neg y$ occurs). A’s failure to absorb the particle causes absorber B to swing to the left (event L occurs), and accordingly the particle is absorbed by B on the left (event x occurs). Absorber B then sends a confirmation wave to the source (event C occurs), which dictates a particle’s state (ψ) in which the chance of emission to the right is ½. Accordingly, we have Loop I, which could be simplified to Loop II (Fig. 1).

C

Loop I 1 **Loop II**

x x

1 1

½ 1

L

½

ψ ψ

Fig. 1: arrows denote causal connections and numbers denote the chance that causes give to their effects.

So Maudlin’s argument is in effect that if Cramer’s theory were possible, Loop II would also be. But, in Loop II the long−run frequency of x in the reference class of states of type ψ is 1, whereas the chance of x in such states is ½. Thus, assuming that long−run frequencies of events should (almost certainly) equal their chance, Crmaer’s theory collapses.

4. Chances and frequencies in causal loops. Maudlin’s assumption that long−run frequencies in causal loops should (almost certainly) equal the corresponding chances is common in linear causation; it is naturally motivated by the so−called ‘law of the large numbers’. Yet, as I will argue below, this assumption is unjustified in causal loops.

Fig. 2.1 C **Fig. 2.2:** C

Loop III

d d

B B

d

i i

A *A*

Fig 2: ‘i’ and ‘d’ denote respectively indeterministic and deterministic causal connections.

The reasoning is as follows (for more details, see Berkovitz 1999, 2000). Consider Fig. 2.1 above, where A is an indeterministic cause of B and B is a deterministic cause of C. To animate things, one may think of a coin−toss in which the angle of my finger at the tossing−time (A) causes the coin to land on ‘heads’ (B), which in turn causes me to perceive ‘heads’ (C).

Suppose that the coin is ‘fair’. Suppose further that the chance of B with A (in the circumstances) is ½. Then, by the law of the large numbers, the long−run frequency of (events of type) B in the reference class of (events of type) A (in the same type of circumstances) will almost certainly be ½. On the other hand, the long−run frequency of B in the reference class of A&C (in the same type of circumstances) will be 1. This is hardly surprising. The reference class A&C is biased; although A (the tossing−angle) is an indeterministic cause of B (“heads”), this class includes only A’s that bring about B’s (namely, only tosses in which I perceive “heads”).

Now, consider Loop III of Fig. 2.2 above, where A is an indeterministic cause of B, B is a deterministic cause of C and C is a deterministic cause of A. Again, to animate things, one may think of a coin−toss in which the angle of my finger at the tossing−time causes the coin to land on “heads”, this result causes me to perceive “heads” and this perception causes the angle of my finger at the tossing time.

Suppose, as before, that the coin is fair and accordingly the chance of B with A is ½. Then, since B is a deterministic cause of C, the long−run conditional frequency of B in the reference class of A&C will be 1. Now, due to the deterministic causal connection from C to A, A and C always appear together. Thus, the long−run frequency of B in the reference class of A will be the same as the long−run frequency of B in reference class of A&C, i.e. 1! And again, a straightforward explanation of why this frequency deviates from ½ is that the reference class of A is biased, *not* that the coin is unfair; for this reference class includes only A’s that bring about B’s.

More generally, (on a plausible interpretation) the law of the large numbers implies that the long−run, conditional frequency of an effect (type) B in an unbiased reference class of its cause (type) A will (almost certainly) equal the chance that B has with A. This law does not imply, however, that such equality should obtain even when the reference class of A is biased. Moreover, as we have seen above, long−run frequencies in biased reference classes would generally deviate from the corresponding chances. But, in causal loops the reference classes of causes are always biased; they only include causes that are caused by their effects.

t L−apparatus R−apparatus

[L2] L1 R2 [R1]

[¬x] [¬y]

Exp. 1 Source Source **Exp. 2**

Fig. 3: dotted lines denote 'trajectories' of particles from sources to apparatuses; arrows denote causal connections; ellipses denote measurement outcomes; rectangles denote measurement apparatuses; and square brackets denote alternative outcomes or settings.

5. On the impossibility of relativistic, parameter−dependent theories. Maudlin's argument fails to establish the impossibility of relativistic, local backwards−causation quantum theories because it relies on an untenable assumption about the nature of probabilities in causal loops. In this section, I will argue that Arntzenius' argument for the impossibility of certain relativistic, non−local quantum theories fails for similar reasons.

5.1. Arntzenius's argument. In most quantum theories, it is the failure of factorisability rather than λ−independence which is responsible for the correlation between distant outcomes. Factorisability can fail in different ways: it can be due to a probabilistic dependence of a nearby outcome on either a distant outcome or a distant setting (or both). The first type of dependence is called 'outcome dependence', whereas the second type is called 'parameter dependence'.

It is frequently claimed that theories that postulate parameter dependence (henceforth, parameter−dependent theories) are more difficult to reconcile with Relativity than theories that postulate outcome dependence. There are various arguments to this effect, but none them is conclusive (Berkovitz 1998b and references therein). In his 1994 (Section 3), Arntzenius argues that any relativistic, parameter−dependent theory is impossible. The argument has the structure of *reductio*: If such theories were possible, certain causal loops would also be. But, argues Arntzenius, the consistency conditions of these loops would require *parameter independence*.

The argument runs as follows. Consider Fig. 3's set−up. The L−measurement of Exp. 1 occurs (invariantly) before the L−measurement of Exp. 2, and the R−measurement of Exp. 1 occurs (invariantly) after the R−measurement of Exp. 2. The outcome of the L−measurement of Exp. 1, either x or ¬x, determines the setting of the L−apparatus of Exp. 2 to be either L1 or L2 respectively. And the outcome of the R−measurement of Exp. 2, either *y* or ¬*y*, determines the setting of the R−apparatus of Exp. 1 to be either R2 or R1 respectively; where L1=R1 and L2=R2. Finally, the L−apparatus of Exp. 1 and the R−apparatus of Exp. 2 (which do not appear in the diagram) are set (fixed) to measure the same quantity.

Due to the relativistic nature of the theory the conditional probability of a nearby outcome given a certain distant setting would be the same in all (inertial) reference frames. Thus, we have Loop IV (see Fig. 4 below). The L−setting influences the (probability of the) R−outcome, which determines the R−setting, which influences the (probability of the) L−outcome, which determines the L−setting. So if parameter−dependent, relativistic theories existed, they would allow Loop IV. But, argues Arntzenius, Loop IV's consistency conditions require *parameter independence*.

Loop IV [L2] L1 R2 [R1]

[¬x] x y [¬y]

Fig. 4: a map of the causal connections of Fig. 3's set−up; arrows indicate causal dependencies.

[Before turning to the details of Arntzenius' argument, two remarks: (i) The probability of x depends not only on the R−setting of Exp. 1, but also on the fixed L−setting of Exp. 1 and the pair's state; and similarly, *mutatis mutandis,* for the probability of y. Yet, to simplify notation, Arntzenius suppresses the pair's state and the fixed settings in these probabilities. (ii) There are two different approaches to the probabilities in Bell models: the 'many−spaces' and the 'big−space' approaches. According to the many−spaces approach, quantum theories do not prescribe probabilities of settings. The settings are not events in the probability space, they rather specify probability spaces; for different settings there are different probability spaces. Arntzenius formulates his argument in the framework of the big−space approach, where it assumed that settings have probabilities and settings and outcomes are both events in the same probability space. He thus expresses parameter dependence by $P(x/R1) \neq P(x/R2)$ and $P(y/L1) \neq P(y/L2)$. The many−spaces approach has some important advantages over the big−space approach. But, to be faithful to Arntzenius' argument I will follow his approach (Berkovitz 1998b, Section 2).]

The details of Arntzenius' argument are as follows. Suppose that pairs' states in Exp. 1 and Exp. 2 are such that $P(x/R1)=P(y/L1)=p_1$ and $P(x/R2)=P(y/L2)=p_2$, where and $p_1 \neq p_2$. Since x causes L1, ¬x causes L2, y causes R2 and ¬y causes R1, we have: $P(x/\neg y)=p_1$, $P(x/y)=p_2$, $P(y/x)=p_1$ and $P(y/\neg x)=p_2$.

Now, (in ideal measurements) there are exactly 4 possible results for joint outcomes: *x*&*y*, *x*&¬*y*, ¬*x*&*y* and ¬*x*&¬*y*. Let us denote the probabilities of these joint outcomes by p_3, p_4, p_5 and p_6 respectively. Expanding the probabilities $P(x/\neg y)$, $P(x/y)$, $P(y/x)$ and $P(y/\neg x)$ in terms of $p_1 - p_6$, we the have:

(1) $p_3/(p_3+p_5)= P(x/y)=P(x/R2)=p_2$; (2) $p_4/(p_4+p_6)= P(x/\neg y)=P(x/R1)=p_1$;

(3) $p_3/(p_3+p_4)= P(y/x)=P(y/L1)=p_1$; (4) $p_5/(p_5+p_6)=P(y/\neg x)=P(y/L2)=p_2$.

As is not difficult to show, equations (1)−(4) jointly imply that $p_1^2(1- p_2)^2 = p_2^2(1-p_1)^2$, which in turn implies that $p_1= p_2$. But, argues Arntzenius, this implies *parameter independence* – $p_1=P(x/R1)=P(x/R2)= p_2$ and $p_1=P(y/L1)=P(y/L2)= p_2$ – in contradition to the assumption that theory is parameter dependent.

5.2. Parameter dependence, chances and frequencies. I will argue below that Arntzenius' argument fails to establish the impossibility of relativistic, parameter−dependent theories. My argument will have two stages. In the first one, I will focus on the interpretation of probabilities in equations (1)−(4). Arntzenius does not specify the nature of these probabilities. But, as I will argue, they should be interpreted as long−run (relative) frequencies.

Based on this claim, I will argue in the second stage that in is argument, Arntzenius in effect demonstrates that parameter dependence does not appear at the statistical level. It is tempting to believe that this lack of dependence implies the impossibility of relativistic, parameter−dependent theories. But, as I will argue below, this is an unwarranted conclusion. For if parameter dependence is to obtain at the level of individual processes, and thus to be defined in terms of single−case, objective probability, Arntzenius' argument only demonstrates that in some loops the parameter dependence would not appear at the statistical level of ensembles of experiments of the same type. On the other hand, if parameter dependence is to hold at the statistical level, parameter−dependent theories do not have to display parameter dependence in such loops. So either way, the demonstration that parameter dependence fails to appear at the statistical level does not show the impossibility of relativistic, parameter−dependent theories.

The detailed reasoning is as follows. Arntzenius presupposes that P(x/R1), P(x/R2), P(y/L1) and P(y/L2) can be expanded in terms of P(x&y), P(x&¬y), P(¬x&y) and P(¬x&¬y): P(x/R1)=P(x/¬y), P(x/R2)=P(x/y), P(y/L1)=P(y/x) and P(y/L2)=P(y/¬x).

Now, parameter−dependent theories do not prescribe definite values for P(x&y), P(x&¬y), P(¬x&y) and P(¬x&¬y). These theories prescribe probabilities of joint outcomes for each of the two experiments: Exp. 1 and Exp. 2. But x (¬x) and y (¬y) are outcomes of measurements of different experiments: x (¬x) is the outcome of the L−measurement of Exp. 1, whereas y (¬y) is the outcome of the R−measurement of Exp. 2 (see Fig. 3).

Moreover, unless interpreted as (relative) frequencies, P(x&y), P(x&¬y), P(¬x&y) and P(¬x&¬y) do not have any definite value in Loop IV: they have different values for different settings. For example, the value of P(x&y) when the setting is L1 and R1 is (generally) different from its value when the setting is L1 and R2.

So unless these probabilities are interpreted as (relative) frequencies, Arntzenius' argument that P(x/R1) equals P(x/R2) will fail to go through; if P(x&y), P(x&¬y), P(¬x&y) and P(¬x&¬y) are not interpreted as frequencies, Arntzenius's assumption that these probabilities have the same value in all the equations (1)−(4) will be untenable. Similarly, *mutatis mutandis*, for P(y/L1) and P(y/L2).

But, if P(x&y), P(x&¬y), P(¬x&y) and P(¬x&¬y) are interpreted as (relative) frequencies, Arntzenius' argument does not establish the claim that relativistic, parameter−dependent theories are impossible.

Here is why. If parameter dependence is to obtain at the level of individual processes, as it is commonly assumed, Arntzenius's argument will demonstrate that parameter dependence fails in loops of type IV only if (long−run) relative frequencies were (almost certainly) equal to the corresponding chances. But, as we have already seen in Section 4, the assumption of such equality is unjustified in causal loops.

But Arntzenius's argument fails to go through even if we assume that parameter dependence is to hold at the level of ensembles of experiments, and accordingly we define it in terms of long−run (relative) frequencies in the reference class of the same type of experiments. Here, an analogy with Loop III (see Fig. 2.2 of Section 4) would be helpful. Recall that in Loop III the angle of my finger in a toss of a fair coin causes the coin to land on "heads", this outcome causes me to perceive "heads" and this in turn causes the angle of my finger at the tossing−time. Recall also that in 'ordinary' tosses (such as in Fig. 2.1's set−up) the conditional, relative frequency of "heads" in the reference class of this tossing−angle is ½, whereas in Loop III the conditional frequency of "heads" in the reference class of the same tossing−angle is 1. Finally, recall that this later probability does not imply that the coin is unfair.

A similar reasoning applies to Loop IV. Define parameter dependence as the conditional, relative frequency of a nearby outcome given a distant setting. Then, the failure of parameter dependence in Loop IV, i.e. the lack of dependence at the statistical level, will not imply that the relativistic theory in consideration is not parameter dependent. The coin in Loop III is fair because of its structure, which in 'ordinary' circumstances (where the tossing−outcome does not cause the tossing circumstances) yields (almost certainly) the same long−run frequency of "heads" and "tails". Similarly, the relativistic theory under consideration is parameter dependent since in 'ordinary' EPR experiments the long−run frequency of nearby outcomes will be dependent on the setting of the distant apparatus. And the failure of this dependence to appear at the statistical level of Loop−type IV does not warrant the opposite conclusion.

So, in short, on either interpretation of the nature of the probabilities in parameter dependence – whether they are single−case, objective probabilities or long−run (relative) frequencies – Arntzenius' argument fails to establish the impossibility of relativistic, parameter−dependent theories.

6. Conclusion. I considered Arntzenius' (1994) and Maudlin's (1994) arguments for the impossibility of certain local and non−local relativistic, quantum theories. I argued that they fail because they rely on untenable assumptions about the nature of probabilities in causal loops. Maudlin's argument relies on the untenable assumption that long−run frequencies of events in causal loops should (almost certainly) equal their chance. Arntzenius' argument relies either on a similar assumption or on the untenable assumption that the imbedding of systems in causal loops would not alter their behavior.

While my arguments above challenge Arntzenius' and Maudlin's reasonings, it does not demonstrate that relativistic quantum theories that allow causal loops are possible. The question of the possibility of such theories depends (in part) on the metaphysical question of the appropriate relation between chances and long−run (relative) in causal loops. And this relation is a matter for further investigation.

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