Time Symmetry in Microphysics*

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ABSTRACT: Physics takes for granted that interacting physical systems with no common history are independent, before their interaction. This principle is time-asymmetric, for no such restriction applies to systems with no common future, after an interaction. The time-asymmetry is normally attributed to boundary conditions. I argue that there are two distinct independence principles of this kind at work in contemporary physics, one of which cannot be attributed to boundary conditions, and therefore conflicts with the assumed T (or CPT) symmetry of microphysics. I note that this may have interesting ramifications in quantum mechanics.

1 Introduction

Consider a photon, passing through a polariser. According to the standard model of quantum mechanics, the state of the photon after the interaction reflects the orientation of the polariser. Not so before the interaction, of course: in quantum mechanics, as elsewhere in physics, we don't expect *preinteractive* correlations.

Writers who notice this time asymmetry—postinteractive correlations, but no preinteractive correlations—sometimes see it as an objection to the standard model of quantum mechanics. To most, however, it seems hardly worthy of notice. True, the asymmetry may be a little puzzling, but its individual components—that interactions may establish correlations, and that there are no preinteractive correlations—seem plausible enough. If we were to try for symmetry, which should we give up? Besides, the principle that there are no preinteractive correlations plays an important role elsewhere in the physics of time-asymmetry, where there is a well-established view to the effect that it is not in conflict with the T-symmetry of underlying physical laws. Thus there seems to be a precedent for the asymmetry we find in quantum mechanics, and no reason, on reflection, to doubt our initial intuitions.

I think the calm is illusory, however, and my aim here is to reveal the troubled waters beneath these rather slippery intuitions. I shall argue that the time asymmetry embodied by the standard model is quite distinct from its supposed analog elsewhere in physics, and cannot be reconciled with the T-symmetry of the laws of physics in the same way. Given T-symmetry, I contend, pre-

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and postinteractive correlations should be on the same footing in microphysics. Any reason for objecting to preinteractive correlations is a reason for objecting to postinteractive correlations, and any reason for postulating postinteractive correlations is a reason for postulating preinteractive correlations.

I emphasise that for the bulk of the paper, the link with quantum mechanics is indirect. The standard model provides vivid examples of the intuitions I want to examine, but my interest is in the intuitions themselves, not in the quantum mechanical examples. However, I close with a comment on the significance of my argument for the puzzles of quantum mechanics. Briefly, its effect seems to be to undermine a crucial presupposition of the standard arguments that quantum mechanics cannot be interpreted in more-or-less classical terms.

2 Two kinds of preinteractive independence

The principle that there are no preinteractive correlations has famous connections with the most striking time-asymmetry in physics, that of the second law of thermodynamics. The connections emerge at two levels. First, Boltzmann's *H*-Theorem derives its time-asymmetry from an assumption concerning the preinteractive independence of interacting microsystems. (This assumption needs to be time-asymmetric, of course, since otherwise the theorem would apply equally in either temporal direction.)

At a more intuitive level, familiar low-entropy systems are associated with striking postinteractive correlations. To make this point vivid, think of the astounding preinteractive correlations we observe if we view ordinary processes in reverse. Think of the tiny droplets of champagne, forming a pressurised column and rushing into a bottle, narrowly escaping the incoming cork. Or think of the countless (genuine!) fragments of the True Cross, making their precisely choreographed journeys to Jerusalem. Astounding as these feats seem, they are nothing but the mundane events of ordinary life, viewed from an unfamiliar angle. Correlations of this kind are ubiquitous in one temporal sense—when they occur *after* some central event, from our usual perspective—but unknown and incredible in the other temporal sense.

In the macroscopic world of ordinary experience, then, the presence of postinteractive correlations and the absence of preinteractive correlations is closely associated with the thermodynamic asymmetry. It is an old puzzle as to where this asymmetry comes from, and especially as to how it is to be reconciled with the apparent T-symmetry of the underlying laws of physics. The orthodox view is that the asymmetry of thermodynamics is a matter of boundary conditions: factlike rather than lawlike, as physicists often say. The contemporary version of this view traces the low-entropy history of familiar physical systems to the condition of the early universe. True, many hope that this early condition will itself be explicable as a natural consequence of cosmological laws, in which case the resulting asymmetry is not strictly factlike. Nevertheless, the success of this program would preserve the intuitive distinction between the symmetry of *local* dynamical laws, and the asymmetry of the boundary conditions supplied

to these symmetric laws in typical real systems.

It seems to be assumed that the kind of asymmetry exemplified by photons and polarisers can be accommodated within this general picture, but I want to show that this is not so. If there is an asymmetry in microphysics of this kind, it cannot be accorded the status of a (locally) factlike product of boundary conditions. This is because, unlike in the thermodynamic case, there is no observational evidence for the required asymmetry in boundary conditions. On the contrary, our sole grounds for thinking that the boundary conditions are asymmetric in the relevant sense is that we already take for granted the principle that there are post- but not preinteractive correlations of the relevant kind. In effect, then, this principle operates in a lawlike manner, in conflict with the assumed T-symmetry of (local) dynamical laws.

The first step is to show that the kind of postinteractive correlation displayed by the photon is quite distinct from that associated with low-entropy systems, such as the champagne bottle. With a little thought, this distinction is easy to draw. For one thing, the correlations associated with low-entropy systems are essentially "communal", in the sense that they involve correlations among the behaviour of very large numbers of individual systems. But the photon correlations are individualistic, in the sense that they involve the simplest kinds of interactions between one entity and another.

Second, the photon case is not dependent on the thermodynamic history of the system comprising the photon and the polariser, or any larger system of which it might form a part. Imagine a sealed black box containing a rotating polariser, and suppose that the thermal radiation inside the box has always been in equilibrium with the walls. We still expect the photons comprising this radiation to establish the usual postinteractive correlations with the orientation of the polariser, whenever they happen to pass through it. The presence of these postinteractive correlations does not require that entropy was lower in the past. By symmetry, then, the absence of matching preinteractive correlations cannot be deduced—at any rate, not directly—from the fact that entropy does not decrease toward the future: a world in which photons were correlated with polarisers before they interacted would not necessarily be a world in which the second law of thermodynamics did not hold.

It will be helpful to have labels for the two kinds of preinteractive independence just distinguished. I'll call the principle that there are no entropy-reducing correlations "H-Independence", in light of its role in the H-Theorem, and the principle that there are no preinteractive correlations between individual microsystems "micro-independence" ("μIndependence", for short).

3 Initial randomness?

I have argued that observational evidence for H-Independence need not be observational evidence for μIndependence—at any rate, not directly. There might be an indirect argument in the offing, however. Perhaps the second law supports some hypothesis about the initial conditions of the universe, an independent

consequence of which is that photons are not correlated with polarisers before they interact. For example, it is often suggested that the explanation for the second law lies in the fact that the initial microstate of the universe is as random as it can be, given its low-entropy macrostate. Wouldn't this hypothesis also explain why photons are not correlated with future polarisers?

In my view this hypothesis is independently unsatisfactory. In particular, it is doubtful whether the required boundary condition can be specified in a nonvacuous way—i.e., other than as the condition that the initial state of the universe is such that the second law holds. (See Price 1996, 42.) General defects to one side, however, the hypothesis turns out to be irrelevant to the issue at hand. In effect, the suggestion is that if systems comprising photons and polarisers are allowed a free choice of the available initial microstates, there can be no general correlation between the states of incoming photon-polariser pairs. If this were true, what would it mean for the ordinary postinteractive correlations? Do these require that the final conditions be less than completely random? Not if we understand the choice to be made from those situations permitted by the relevant physical laws—in other words, from the phase space of the system in question. Of course, if we think of nature making its choice from some larger set of possibilities, then the laws themselves constitute restrictions on the available options. Only choices in accordance with the laws are allowed. But a random choice from phase space (or, equivalently, from the set of trajectories of a deterministic system) is by definition a choice from among (all and only) the options allowed by the laws.

Thus lawlike postinteractive correlations are not incompatible with randomness of final conditions. By symmetry, matching preinteractive correlations would not require non-random initial conditions. Hence μIndependence receives no support from the hypothesis that initial randomness explains the thermodynamic asymmetry.

4 Colliding beams?

There is another argument in the literature to the effect that there is indirect observational evidence for μIndependence. It turns on the idea that by postulating μIndependence, we are able to explain certain observable phenomena. I think this argument is due originally to O. Penrose and R. Percival (1962), who formulate a principle of preinteractive independence they call the Law of Conditional Independence. As their terminology indicates, Penrose and Percival take this to be a lawlike principle. In favour of this view, they argue that the principle is able to explain a variety of otherwise inexplicable irreversible processes.

The claim that Conditional Independence is lawlike has not been widely accepted, but it does seem a common view in physics that Penrose and Percival's examples provide indirect observational evidence for preinteractive independence. A typical example concerns the scattering which occurs when two tightly organised beams of particles are allowed to intersect. The argument is

that this scattering is explicable if we assume that there are no prior correlations between colliding pairs of particles (one from each beam)—and hence that the scattering pattern reveals the underlying independence of the motions of the incoming particles.

In fact, however, μIndependence is neither necessary nor sufficient here. The explanation rests entirely on the absence of entropy-reducing correlations between the incoming beams—i.e. on H-Independence—not on μIndependence at the level of individual particle pairs. In other words, the asymmetry involved in these cases is nothing more than the familiar thermodynamic asymmetry, from which—as we have seen—μIndependence is supposed to be distinct.

I'll offer short and long arguments for this conclusion. The short argument simply appeals to cases in which it seems intuitively clear that there is no microscopic asymmetry—Newtonian particles, for example. In these cases there seems to be nothing to sustain any asymmetry at the level of individual interactions, and yet we still expect colliding beams to scatter. This suggests that the scattering is associated with the lack of some global correlation, not with anything true of individual particle pairs.

The longer argument goes like this. We suppose that there is a microscopic asymmetry of μIndependence, distinct from the correlations associated with the thermodynamic asymmetry, and yet compatible with the T-symmetry of the relevant dynamical laws. We then construct a temporal inverse of the scattering beam experiment, and show that it displays (reverse) scattering, despite the assumed absence of the postinteractive analog of μIndependence. By symmetry, this shows that μIndependence is not necessary to explain the scattering observed in the usual case. Finally, a variant of this argument shows that μIndependence is also insufficient for the scattering observed in the usual case.

If μIndependence were necessary for scattering, in other words, then scattering would not occur if the experiment were run in reverse. It is difficult to replicate the experiment in reverse, for we don't have direct control of final conditions. But we can do it by selecting the small number of cases which do satisfy the desired final conditions from a larger sample. We consider a large system of interacting particles of the kind concerned, and consider only those pairs of particles which emerge on two tightly constrained trajectories (one particle on each), having perhaps interacted in a specified region at the intersection of these two trajectories (though not with any particle which does not itself emerge on one of these trajectories). We then consider the distribution of initial trajectories, before interaction, for these particles. What is the most likely distribution? If the dynamical laws are T-symmetric, then it must be simply the distribution which mirrors the predicted scattering in the usual case.

The argument can be made more explicit by describing a symmetric arrangement, subsets of which duplicate both versions of the experiment. Consider a spherical shell, divided by a vertical plane. On the inner face of the left hemisphere is an arrangement of particle emitters, each of which produces particles of random speed and timing, directed towards the centre of the sphere. In the right hemisphere is a matching array of particle detectors. Dynamical T-symmetry implies that if the choice of initial conditions is random, the global history of

the device is also time-symmetric: any particular pair of particle trajectories is equally likely to occur in its mirror-image form, with the position of emission and absorption reversed.

We can replicate the original collimated beam experiment by choosing the subset of the global history of the device containing particles emitted from two chosen small regions on the left side. Similarly, we can replicate the reverse collimated beam experiment by choosing the subset of the history of the entire device containing particles absorbed at two chosen small regions on the right side. In the latter case, the particles concerned will in general have been emitted from many different places on the left side. This follows from the fact that the initial conditions are a random as possible, compatible with the chosen final conditions. Thus we have scattering in the initial conditions, despite the assumed lack of postinteractive μIndependence between interacting particles.

Thus if there were postinteractive correlations of the kind denied to the preinteractive case by μIndependence, they would not stand in the way of scattering in the reverse experiment—scattering in that case is guaranteed by the assumption that the initial conditions are as random as possible, given the final constraints. By symmetry, however, this implies that μIndependence is not necessary to produce scattering in the normal case. We would have scattering without μIndependence, provided that the choice of trajectories is as random as possible, given the initial constraints. (Don't suggest that this is the same thing as μIndependence. If that were true, μIndependence would not fail in the postinteractive case, and there not be the assumed microscopic asymmetry.)

A third version of the experiment can be used to show that μIndependence is not sufficient to explain what happens in the normal case. Assume μIndependence again, and consider the subset of the first experiment in which we have collimation on the right, as well as the left—in other words, in which we impose a final condition, as well as an initial condition. In this case, we have no scattering, despite μIndependence. Again, it is no use saying that the imposition of the final condition amounts to a denial of μIndependence: if that were true, the asymmetry of μIndependence in the normal case would amount to nothing more than the presence of a low-entropy initial condition, in conflict with the supposition that μIndependence differs from H-Independence.

In other words, μIndependence is both insufficient and unnecessary to explain the phenomena observed in these scattering experiments. The differences between the various versions of the experiment are fully explained by the different choices of initial and final boundary conditions. The asymmetry of the original case stems from the fact that we have a low-entropy initial condition (consisting in the fact that the beam are initially collimated) but no corresponding final condition. The issue as to why this is the case that occurs in nature is a sub-issue of that of the origins of the thermodynamic asymmetry in general. It has nothing to do with any further asymmetry of kind described by μIndependence.

5 What to do about μIndependence

It seems that as it currently operates in physics, then, μIndependence is not an a posteriori principle derived from observation, but a lawlike principle in its own right. We don't *observe* that the incoming photon is not correlated with polariser through which it is about to pass. Rather, we rely on a tacit meta-law that laws enforcing preinteractive correlations would be unacceptable. In a sense, then, we do take it for granted that there is an asymmetry in the boundary conditions of the kind required by μIndependence: not because we have empirical evidence for such an asymmetry, however, but only because we have framed the laws in the light of μIndependence. We allow dynamical principles producing postinteractive correlations, while disallowing their preinteractive twins.

Conceding that μIndependence is lawlike does not improve its prospects, of course; it simply 'fesses-up to the principle's current role in microphysics. In one important sense it makes its prospects very much worse, for as a lawlike principle, μIndependence conflicts with T-symmetry. We might be justified in countenancing such a conflict if there were strong empirical evidence for a time-asymmetric law, but the supposed evidence for μIndependence turns out to rely on a different asymmetry altogether.

What are the options at this point? First, we might look for other ways of defending μIndependence. Unless this evidence is a posteriori, however, its effect will be simply to deepen the puzzle about the T-asymmetry of microphysics. Moreover, although there is undoubtedly more to be said about the intuitive plausibility of μIndependence, I suspect that the effect of further investigation is to explain but not to *justify* our intuitions. For example, the intuitive appeal of μIndependence may rest in part on a feature of human experience, the fact that in practice our knowledge of things in the physical world is always postinteractive, not preinteractive. The exact explanation of this asymmetry is rather tricky. It seems to depend in part on our own time-asymmetry as structures in spacetime, and in part on broader environmental aspects of the general thermodynamic asymmetry. Whatever its exact provenance, however, it seems to provide no valid grounds for extending the intuitions concerned to microphysics.

Similarly, as I've argued elsewhere (1996, 181–4), some apparent postinteractive dependencies turn out to be associated with a temporal asymmetry in counterfactual reasoning—roughly, the fact that we "hold fixed" the past, when considering the consequences of counterfactual conditions. Given a conventional account of this aspect of counterfactual reasoning, the asymmetries concerned are thus demystified, in the sense that they are shown to require no independent asymmetry in the physical systems concerned. Again, some of the intuitive appeal of μIndependence is thereby accounted for, but in a way which does nothing to clarify the puzzle of the photon case.

Another response to the puzzle would be to try to restore T-symmetry in microphysics by excising postinteractive correlations, rather than by admitting preinteractive correlations. The standard model of quantum mechanics might be first in line, for example. The surgery required is likely to be rather radical,

however. Without postinteractive correlation of some sort, how is it possible for a measuring device to record information about an object system? That aside, the move seems misguided. It does nothing to justify μIndependence, and restores symmetry by creating two puzzles where previously we had one.

In my view, the only option which really faces up to the problem is that of admitting that our intuitions might be wrong, and that μIndependence might indeed fail in microphysics. I want to finish with a few remarks on the possible relevance of this option in quantum mechanics. In order to clarify the force of these remarks, I emphasise again that up to this point, my references to quantum mechanics have been somewhat inessential. The standard model of quantum mechanics provides the most vivid examples of an asymmetry we find it easy to take for granted in microphysics, but the case against this asymmetry has been essentially classical. The main point is that despite common opinion to the contrary, it is not associated with the classical asymmetry of thermodynamics. In effect, then, the case against μIndependence constitutes a prior constraint on the interpretation of quantum mechanics.

6 μIndependence and quantum mechanics

Surprisingly, μIndependence turns out to be a fundamental assumption of the main arguments taken to show that the quantum world is puzzlingly nonclassical. In particular, Bell's Theorem depends on the assumption that the state of an object system is independent of the setting of a measurement device, prior to their interaction. Thanks to μIndependence, this independence assumption has often seemed so uncontentious as to pass without comment. Bell himself considered relaxing it, but even he tended to think about this possibility in a way which doesn't conflict with μIndependence. (His suggestion, which he called "superdeterminism", was that the correlation might established by an additional common cause in the past, not simply in virtue of the existing interaction in the future; see Bell et. al., 1985.)

More recent arguments for nonlocality (the GHZ cases; see e.g., Clifton, Pagonis and Pitowsky 1992) also depend on this independence assumption. Without μIndependence, then, there seems to be no firm reason to think that quantum mechanics commits us to nonlocality. Many commentators have noted that in principle, the Bell correlations are easily explicable if hidden common causes may lie in the future, as well as in the past. My point is that if μIndependence is rejected on classical grounds, this is precisely what we should expect.

There is a similar impact on the no hidden variable theorems (e.g. Kochen and Specker 1967), which argue that no system of pre-existing properties could reproduce the predictions of quantum mechanics, at least in certain cases. μIndependence serves to justify the assumption that a single hidden state must reproduce the quantum predictions for any *possible* next measurement. If the hidden state is allowed to vary with the nature of the measurement, the problem is relatively trivial. (In Bohm's 1952 hidden variable theory, the trick is to allow measurement to have an instantaneous effect on the hidden variables;

again, however, μIndependence underpins the assumption that the effect must be instantaneous, rather than advanced.) Abandoning μIndependence might thus resuscitate the hidden variable approach, and with it an old solution to the measurement problem: If collapse corresponds merely to a change in information, it is unproblematic.

Thus μIndependence plays a crucial role in the main arguments taken to show that quantum mechanics has puzzling nonclassical consequences. Imagine how things would have looked if physics had considered abandoning μIndependence on symmetry grounds, before the development of quantum mechanics. Quantum mechanics would then have seemed to provide an additional argument against μIndependence, by reductio: given quantum mechanics, μIndependence implies such absurdities such as nonlocality and the measurement problem. Against this background, then, experimental confirmation of the Bell correlations would have seemed to provide empirical data for which the best explanation is that μIndependence does fail, as already predicted on symmetry grounds.

Of course, from a contemporary standpoint it is difficult to see things in these terms. Leaving aside our intuitive commitment to μIndependence, the quantum puzzles have lost much of their capacity to shock—familiarity has bred a measure of contentment in physics, and the imagined reductio has lost its absurdum. Regaining a classical perspective would not be an easy step, or one to be attempted lightly, but it does seem worth entertaining. By abandoning a habit of thought which already seems to conflict with well-established principles of symmetry, we might free quantum mechanics of consequences which once seemed intolerable in physics, and might do so again.

7 References

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