Evidence for Interactive Common Causes. Resuming the Cartwright-Hausman-Woodward Debate

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13th Mar 2021
(Version 1.82)

The most serious candidates for common causes that fail to screen off ('interactive common causes', ICCs) and thus violate the causal Markov condition (CMC) refer to quantum phenomena. In her seminal debate with Hausman and Woodward, Cartwright early on focussed on unfortunate non-quantum examples. Especially, Hausman and Woodward's redescriptions of quantum cases saving the CMC remain unchallenged. This paper takes up this lose end of the discussion and aims to resolve the debate in favour of Cartwright's position. It systematically considers redescriptions of ICC structures, inlcuding those by Hausman and Woodward, and explains why these do not provide an appropriate description, when quantum mechanics is true. It first shows that all cases of purported quantum ICCs are cases of entanglement and then, using the tools of causal modelling, it provides an analysis of the quantum mechanical formalism for the case that the collapse of entangled systems is best described as a causal model with an ICC.

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1 Introduction

The common wisdom is that common causes screen off their effects: If two variables $\boldsymbol{a}$ and $\boldsymbol{b}$ have a common cause $\boldsymbol{c}$ and are not directly causally related (neither is $\boldsymbol{a}$ a cause of $\boldsymbol{b}$ nor vice versa), then $\boldsymbol{a}$ and $\boldsymbol{b}$ are marginally correlated but statistically independent given knowledge about $\boldsymbol{c}$. This statistical characterization is widely believed to be a central feature of common causes and is captured by the causal Markov condition (CMC, a generalization of Reichenbach's principle of the common cause; Reichenbach 1956; Hitchcock and Rédei 2020, §7), which is part of our best theories of causation (the CMC is an axiom of the theory of causal Bayes nets by Spirtes et al. 1993 and Pearl 2000, and a purported consequence of the interventionist theory of Woodward 2003).

Some philosophers have challenged this view by a number of counterexamples: They have adduced situations in which conditional on the common cause the correlation persists and in this sense the common cause fails to screen off its effects from another. Referring to Salmon's interactive forks (1978; 1984), which were the first putative counterexamples, we shall call such common causes that do not screen off 'interactive common causes' (ICC) and qualify usual common causes, that do screen off, as 'conjunctive common causes'. Today it is well-known that many cases of purported ICCs, among them Salmon's original proposals, are artefacts of incorrect descriptions of the system in question (cf. Spirtes et al. 2000, 35f): described properly, all common causes in such systems do screen off and the CMC holds. We call such cases 'apparent ICCs' as opposed to 'genuine ICCs' that persist even in a correct description. While apparent ICCs are an epistemological challenge and occur frequently in scientific practice, it is of course genuine ICCs, violating the CMC, which are conceptually most interesting.

It is controversial whether *all* reported cases of ICCs are apparent:

(Q1) Are there genuine ICCs in our world?

This is the question of the present paper. Since the debate about possible violations of the CMC by common causes is ramified, I emphasize that (Q1) is to be discerned from the following related but logically independent[1] questions:

(Q2) Do all causal systems fulfil the CMC?

(Q3) If there is a failure of the CMC by genuine ICCs, how can one explain the correlation between the effects of the ICC (which are stronger than a usual common causes would explain)?

(Q4) Do all causal systems fulfil modularity, i.e. the condition, roughly, that every effect in a system comes about by its own separate mechanism?

(Q5) If there is a failure of modularity by genuine ICCs, how can one explain the failure of modularity?

(Q6) Does modularity imply the CMC?

In this paper we focus on (Q1) without treating (Q2)–(Q6).

I shall answer (Q1) in the affirmative by arguing that not all cases of purported ICCs can plausibly be redescribed such that the CMC holds: *There are systems in our world that involve a causal anomaly that genuinely has the structure of an ICC.* Such genuine ICCs are not the result of a misdescription, but are real structures in our world. This is the main claim of the present paper and I stress that I shall not argue beyond this claim: Especially, I shall not assess what the existence of genuine ICCs in certain systems means for these systems' status of being causal or not (Q2 and Q4), nor shall I provide an explanation of why screening-off and modularity fail (Q3 and Q5), and especially I shall not examine whether ICCs provide an acceptable causal explanation (or any explanation at all) for the correlations that are stronger than usual common causes can explain (Q3). Here, I am just discussing the evidence for the case that there are genuine ICC structures.

Since ICCs violate usual principles of causal modelling – by definition the CMC and modularity and, as a matter of fact, as I shall explain, also independent fixability – I further emphasize that in this paper I neither treat the question what the existence of ICC structures implies for the status of these principles of causal modelling. There are two rough options: either systems with genuine ICCs are not causal and hence the principles of causal modelling are not affected since they should not be applied to such systems. Or such systems are causal, and the principles of causal modelling are violated and need to be revised. The reader may have a preference for the one or the other option but I shall not attempt to decide between them in this paper.

My main claim that there are genuine ICCs is not new. After the very first examples by Salmon and others had turned out to be apparent ICCs, it were van Fraassen (1980, 1982a,b) and especially Cartwright (1988, 1989) who provided the most promising candidates for genuine ICCs violating the CMC. The common characteristic of the examples is that common causes act *indeterministically* and produce their effects in pairs (e.g. due to conservation laws). Since indeterminism is required, realistic examples refer to the quantum domain (in a usual indeterministic collapse interpretation): A prominent

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[1] Especially, it makes sense to answer both (Q1) and (Q2) in the affirmative, which is to say that there are systems with ICCs, but that such systems are not causal.

example is the indeterministic decay of a molecule into two halves, where the momenta (or the size) of the halves is perfectly anti-correlated, but the state prior to decay does not screen off this strong correlation; another is the measurement of entangled properties in EPR experiments.

The position that there are genuine ICCs has not been very popular in the causal modelling literature, and has been defended for the last three decades or so nearly exclusively by Nancy Cartwright (though probably with some silent sympathizers; recent advocates are Näger 2014, 2016 and Schurz 2017). While her early writings on the subject were based on clear quantum cases of ICCs, Cartwright later mainly focussed on the example of a chemical factory (first in Cartwright 1993, and repeated in many following publications), which let her defence of ICCs turn out not as strong as it could have been, for at least two reasons. First, unlike the factory example, the quantum cases are particularly strong because they rest on a precise mathematical description that is empirically well-confirmed. Second, combining the claim with other controversial theses has watered down the position. In particular, the case of the chemical factory—assumes controversial macro indeterminism, which has been shrugged off as fictitious (Glymour 1999; Hausman and Woodward 2004a). Finally, Cartwright's defence suffered from the fact that she shifted focus from the central question (Q1) to related questions such as (Q2).

The debate between Cartwright on the one, arguing for genuine ICCs, and Hausman and Woodward on the other side, defending the CMC against Cartwright's criticism, is the deepest and most intense debate about ICCs up to date, treating or at least touching upon all of questions (Q1)–(Q6); it took place in a series of long and intricate papers (Hausman and Woodward 1999; Cartwright 2002; Hausman and Woodward 2004a,b; Cartwright 2006) and illustrates the shift in discussion. In their first response to Cartwright, Hausman and Woodward (1999) extensively discuss the example of entangled quantum states and propose that even the quantum examples only apparently violate the CMC because the causal structure is misrepresented. In her subsequent answers, however, Cartwright does not reply to these questionable proposals (without giving reasons), and the debate focusses on her factory example, that Hausman and Woodward easily dismiss, and then continues to treat questions (Q2)–(Q6).

In this way it happened that up to now Hausman and Woodward's proposals that would save the CMC in the quantum realm are uncontradicted; a debate about the plausibility of their claims is still missing. In general, the debate about proposed quantum ICCs has never been led conclusively and, since quantum ICCs are the most serious candidates for genuine ICCs, there exists considerable unclarity whether there are such ICCs.

This paper investigates in detail the central evidence for and against assuming a genuine ICC model for the quantum cases. Against arguments by Hausman and Woodward (and others) I defend the view that, if quantum theory is true, there are genuine ICCs. In this sense this paper aims to catch up what Cartwright could have said in response to Hausman and Woodward 20 years ago and to make her case for ICCs as strong as it can be made. My main argument will be an analysis of the quantum mechanical formalism that yields an appropriate causal model for the theory. In this way, the present work is also a contribution to the emerging field of quantum causal modelling.

Since there are different interpretations of the quantum realm I should mention at the outset that this paper presupposes a usual collapse interpretation of quantum theory (as it is made precise in the GRW theory, Ghirardi et al. 1986), according to which quantum theory is complete (and especially does not assume hidden variables) and certain processes in the quantum realm, particularly measurements with macroscopic devices, are indeterministic in an ontic sense. Note that the question whether there are ICCs is controversial even given this assumption.

The paper is organised in three main sections. After a short characterization of ICCs that also introduces some terminology (section 2), I review diverse phenomena from the quantum realm that purportedly are serious candidates for genuine ICCs and argue that all such examples are cases of entanglement (section 3). The question whether there are genuine ICCs then reduces to the question whether entangled systems involve genuine ICCs. Analyzing the quantum mechanical formalism, I argue that entangled systems involve genuine ICCs. I also discuss in detail why the main rival proposals are not viable (section 4).

2 Characterizing ICCs

2.1 Cartwright's paradigmatic case and the decaying molecule

Cartwright proposes one of the paradigmatic examples in the debate. She describes the situation that a 'particle collides with an atom and the atom emits two new particles as a consequence' (Cartwright 1988, 184). Here we consider a slightly different variant of her example[2] that there is a molecule in an unstable state z_1, which is disposed to decay and at some point decays into two even smaller objects, say, two atoms of the same kind. Due to the conservation of momentum, it is determined that the atoms move in opposite direction, such that their total momentum remains zero. What is indetermined about this process is along which direction the atoms fly off. (The laws of quantum physics are consistent with the fact that the atoms fly off in any direction, as long as they are heading in opposite directions.) Cartwright assumes the most simple case that there are only two possible directions (0 or 1), i.e. either, with a certain probability q, we have the momenta x_0 and y_0 (with $x_0 = -y_0$), or, with probability $1 - q$, we have the momenta x_1 and y_1 (with $x_1 = -y_1$; see Figure 1). By these assumptions, the probability distribution of this case is

$$P(x_0 y_0 | z_1) = q \qquad P(x_0 y_1 | z_1) = 0 \qquad P(x_1 y_0 | z_1) = 0 \qquad P(x_1 y_1 | z_1) = 1 - q, \tag{1}$$

which implies the conditional probabilities for each single atom,

$$P(x_0 | z_1) = q \qquad P(y_0 | z_1) = q \qquad P(x_1 | z_1) = 1 - q \qquad P(y_1 | z_1) = 1 - q. \tag{2}$$

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[2] My reason to assume a variant is that momentum conservation is relevant for the Cartwright's formal analysis; however, in her example, where two particles are emitted by an atom, momentum need not strictly be conserved for the *pair* of particles because the atom can resorb some momentum as well.

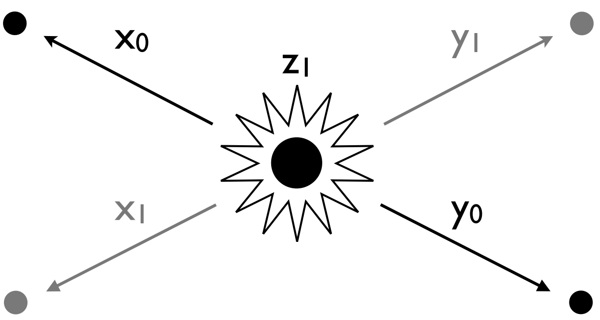

Figure 1: A molecule in state z_1 decays indeterministically into two oppositely moving parts along one of two directions

Here we have described physical properties or states, respectively, by values of variables $x_{0/1}$, $y_{0/1}$ and z_1. We shall denote the corresponding variables by bold symbols $\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{z}$ and describe causal structures, as is usual in causal modelling, as between variables. Assuming, as it seems natural in the present case, that the state $\boldsymbol{z}$ of the molecule prior to decay both causes the momentum $\boldsymbol{x}$ as well as the momentum $\boldsymbol{y}$ of the emerging smaller molecules, and that these momenta do not influence each other after decay, yields a common cause structure $\boldsymbol{x} \leftarrow \boldsymbol{z} \rightarrow \boldsymbol{y}$. Since causal models consist of a causal structure (typically, a directed acyclic graph involving a set of variables as nodes and directed edges between the nodes such that there are no loops of arrows) and a probability distribution over the variables, this completes the causal model of the decaying molecule.

In causal modelling one usually requires certain axioms that constrain which probability distributions are consistent with which structures. The central assumption is the

> **Causal Markov condition (CMC):**[3] A variable $\boldsymbol{a}$ in a given causal structure is probabilistically independent of its non-effects (NE) conditional on its direct causes (DC):
>
> $$\big[\boldsymbol{B} = \mathrm{NE}(\boldsymbol{a}) \;\wedge\; \boldsymbol{C} = \mathrm{DC}(\boldsymbol{a})\big] \quad \rightarrow \quad \mathrm{I}(\boldsymbol{a}, \boldsymbol{B}|\boldsymbol{C}).$$

The CMC is typically required to hold for all variables in a causal structure represented by a directed acyclic graph. For a common cause structure $\boldsymbol{x} \leftarrow \boldsymbol{z} \rightarrow \boldsymbol{y}$ the condition requires the statistical independence

$$I(\boldsymbol{x}, \boldsymbol{y}|\boldsymbol{z}) \leftrightarrow \forall x, y, z : P(xy|z) = P(x|z)P(y|z), \tag{3}$$

which is also denoted as '$\boldsymbol{z}$ screening off $\boldsymbol{x}$ from $\boldsymbol{y}$'.

A simple comparison between (1) and (2), however, yields that according to the causal model describing Cartwright's example, the value z_1 of the common cause, the considered

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[3] cf. Spirtes et al. 1993, sec. 3.4.1; Pearl 2000, p. 19

state of the molecule before decay, in general does not screen off the perfect correlation between the atoms' momenta x_0 and y_0:

$$P(x_0 y_0 | z_1) = q \neq q^2 = P(x_0|z_1)P(y_0|z_1). \tag{4}$$

The common cause model of Cartwright's decaying molecule thus clearly violates the CMC.

Let me make two comments. First, the result that z_1 does not screen off does not depend on the exact value of q, as long as q is not 0 or 1. When q is 0 or 1 ('determinism'), however, the equations reveal that screening-off holds trivially. Hence, indeterminism is a necessary ingredient for ICCs.

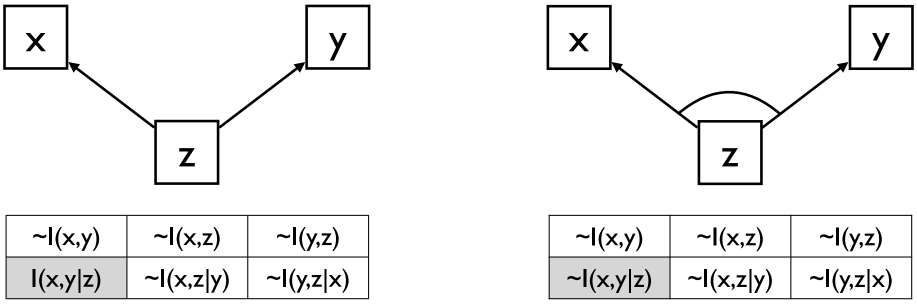
It is an open question whether proposed ICCs such as the decaying molecule, besides violating the CMC, violate the condition of *modularity*. The condition, which has been introduced by Hausman and Woodward (1999), expresses the idea that every effect in a causal model comes about by its own separate process or mechanism. In mathematical causal models this is reflected in the fact that every variable has its own separate equation that determines its value by the values of its causes. If modularity holds, every causal process of the model is, in principle, *independently disruptable*, i.e. can be stopped without interfering with any other causal process that is not an effect of the stopped process. Hausman and Woodward (1999, 2004b) claim that modularity (plus some additional conditions) imply the CMC. If this were true, an ICC violating the CMC would also violate modularity; however, Cartwright (2002, 2006) and Steel (2006) criticise the implication and it seems an open question whether the proposed cases of ICCs in fact violate modularity. We shall come back to this question in Section 4.3.3.

2.2 Conjunctive vs. interactive common causes

Here we shall not attempt at a general definition of ICCs in terms of necessary and sufficient conditions, which would be against the spirit of an axiomatic characterization of causal structures that causal modelling by causal Bayes nets provides (cf. Glymour 2004). Rather, we discern and characterize conjunctive and interactive common causes via general paradigmatic causal models, of which the model for the decaying molecule is an instance.

The most simple, paradigmatic causal models with these types of common causes are shown in figure 2a and 2b. The models are to be understood as sufficient conditions: If there is a causal structure as indicated and the statistics is as indicated, then $\boldsymbol{z}$ is a conjunctive or interactive common cause, respectively. Interactive common causes are marked by drawing an arc between the outgoing arrows.

These paradigmatic cases involving three variables might also be found as substructures of causal models. Note further that by these paradigmatic cases we have not said what it means to be an ICC in more complex cases (especially when $\boldsymbol{x}$ and $\boldsymbol{y}$ are additionally connected by a directed causal path or if there are further common causes of $\boldsymbol{x}$ and $\boldsymbol{y}$) — this would require an axiomatic characterization. Since here we are about to argue that there are ICCs at all, it suffices to show that there are ICCs of the paradigmatic kind; so in the rest of the paper we shall concentrate on the simple paradigmatic causal structures.



~I(x,y)	~I(x,z)	~I(y,z)
I(x,y|z)	~I(x,z|y)	~I(y,z|x)

~I(x,y)	~I(x,z)	~I(y,z)
~I(x,y|z)	~I(x,z|y)	~I(y,z|x)

(a) Common cause structure (b) Interactive common cause

Figure 2: Two kinds of common cause models

An ICC $\boldsymbol{z}$ in a causal model M is *apparent* when according to the system S (a system in the world, a model of a theory or a causal model itself) that M describes, $\boldsymbol{z}$ is in fact a conjunctive common cause, i.e. M misrepresents the ontology of S with regard to $\boldsymbol{z}$'s interactivenes. An ICC is *genuine* when it is not apparent.

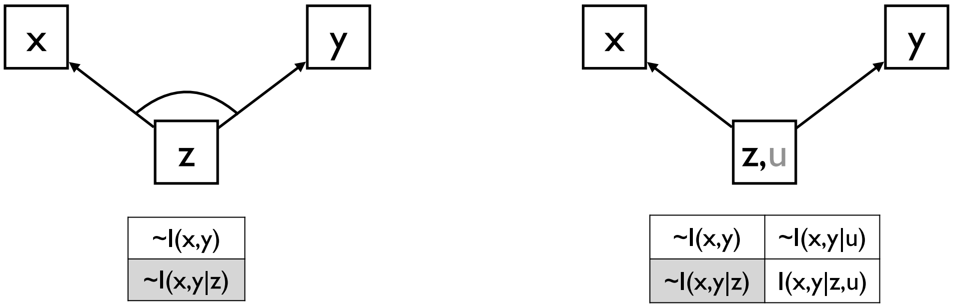
It is well-known that one can generate models with ICCs by misrepresenting the causal structure in question. Figure 3 provides an overview of the central cases. It shows structures with the three variables $\boldsymbol{z}$, $\boldsymbol{x}$ and $\boldsymbol{y}$ that yield $\boldsymbol{z}$ as an apparent interactive common cause of $\boldsymbol{x}$ and $\boldsymbol{y}$ (a), if one wrongly omits those elements of the structures that are depicted in gray (b–h). We shall comment on each of these possible misrepresentations when discussing the causal structure of the quantum mechanical formalism below.

3 Promising candidates for genuine ICCs

3.1 Quantum ICCs are the most serious candidates for genuine ICCs

There is a number of purported cases that have exactly the same formal structure as the paradigmatic example (or can at least be simplified to have that structure). One needs to distinguish fictitious examples from realistic ones: The former are simply cooked up by assuming a suitable formal structure, however, without providing (enough) evidence that in fact there are such systems in our world (e.g. can Fraassen's dividing bullet and Cartwright's chemical factory have been claimed to be of this kind). Realistic examples, in contrast, agree in their structure with our best scientific theories or models, and it is controversial whether there are such examples.

Since indeterminism is a necessary ingredient for ICCs, the scientific background theory required for the realistic cases must be indeterministic. While many special sciences involve theories or models with indeterministic dynamics, such cases can easily be dismissed as

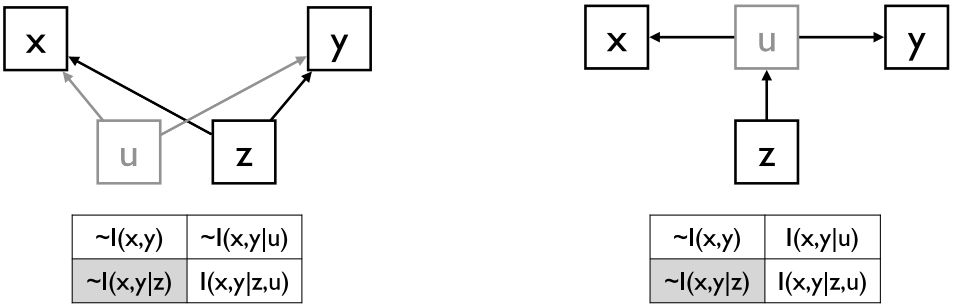


~I(x,y)	
~I(x,y|z)	

~I(x,y)	~I(x,y|u)
~I(x,y|z)	I(x,y|z,u)

(a) Interactive common cause structure

(b) Fine-grained common cause structure

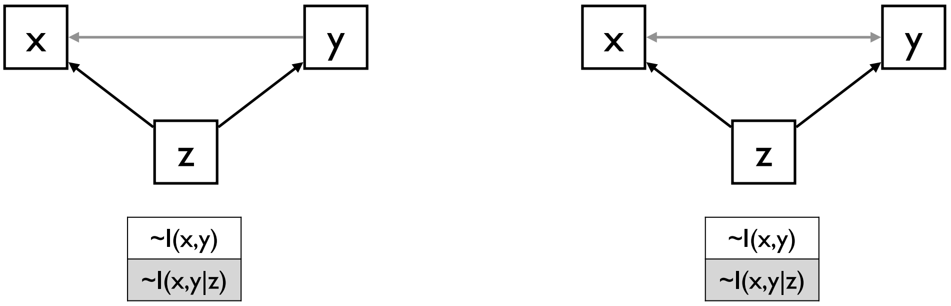


~I(x,y)	~I(x,y|u)
~I(x,y|z)	I(x,y|z,u)

~I(x,y)	I(x,y|u)
~I(x,y|z)	I(x,y|z,u)

(c) Latent common cause structure

(d) Intermediate common cause structure



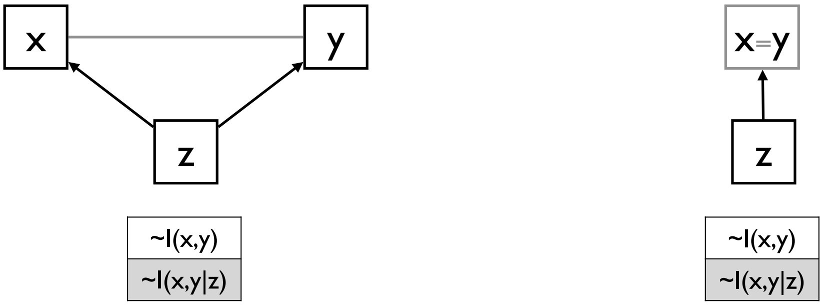
~I(x,y)	
~I(x,y|z)	

~I(x,y)	
~I(x,y|z)	

(e) Direct cause structure

(f) Cyclic direct cause structure

Figure 3: Generation of apparent interactive common causes. Omitting the gray elements in the causal structures (b)–(j) yields an apparent interactive common cause (a).



(g) Non-separable structure

(h) Single effect structure 1: unit by identity

(i) Single effect structure 2: unit by composition

(j) Single effect structure 3: unit by dependent fixability

Figure 3: Generation of apparent interactive common causes [continued]

involving only *epistemic* indeterminism, i.e. a more detailed description, which might epistemically not be accessible, would reveal that determinism and consequently screening-off holds.[4] Whether this is true or not, the argument threatens the genuity of most macro cases from the special sciences since one neither has clear arguments why the indeterminism in question is ontic.

In contrast, quantum theory (in a standard collapse reading) is ontically indeterministic and since the theory furthermore happens to be the most successful one in scientific history, quantum ICCs are the most serious examples for genuine ICCs.[5]

3.2 Prima facie classification of proposed quantum ICCs

Prima facie, there seem to be four basic classes of quantum ICCs. (i) Cartwright's example of an unstable molecule (of which there are many instances in chemistry) belongs to the category of *decay or division*. Radioactive α-decay is another clear case in this category. The ICC candidate is the unstable state of the radium nucleus that, in a certain amount of time, indeterministically decomposes into a helium nucleus and a radon nucleus, or not. Either both the radium and the radon nucleus are present or both are not – which fulfils the typical formal scheme of an ICC.

(ii) Other types of radioactivity like β-decay (a nucleus emits an electron and an anti-electron neutrino and a neutron inside the nucleus is transformed into a proton), or γ-decay (where a nucleus emits a high-energy photon and enters a lower energy state), might rather be subsumed under the class of *emission* processes: A system emits with a certain probability another system and thereby enters a new state itself. Another example would be atoms (or molecules) in an excited state, which in a certain time span with probability q emit a photon and (due to energy conservation) transit to their ground states, or (with probability $1-q$) do not emit a photon and just remain in the excited state.

(iii) Examples for a third class, *jointly generated objects*, are numerous in high energy physics, where collisions of two particles produce with a certain probability two (or more) particles, but due to conservation laws (especially energy and momentum, but also charge, spin, isospin, etc.) only certain combinations of particles can occur. For instance, one might have the case that collisions of an electron with its anti-particle (positron) with probability q produce an up quark and its anti-particle (up anti-quark) while with probability $1-q$ the collision produces a down quark and its anti-particle (down anti-quark).

(iv) Fourth, *entangled states*

$$z'_1 = \sqrt{q}|x_0\rangle|y_0\rangle + \sqrt{1-q}|x_1\rangle|y_1\rangle, \tag{5}$$

as they are prepared in EPR/B experiments (maximally entangled for $q = \frac{1}{2}$, e.g. the

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[4] The misdescriptions can either involve more fine-grained variables (Figure 3b) or additional common causes (Figure 3c and d).

[5] Further serious candidates, which, however, we do not discuss in this paper, might be those cases of macro ICCs, where quantum indeterminism leverages to the macro realm.

entangled polarization state of two photons), yield exactly the same probability distribution as in Cartwright's example (when measured at parallel settings): At measurement, the entangled state collapses onto one of the two product states

$$\begin{aligned} &|x_0\rangle|y_0\rangle \qquad \text{with probability } q \quad \text{or} \\ &|x_1\rangle|y_1\rangle \qquad \text{with probability } 1-q. \end{aligned} \tag{6}$$

Since it is well-known that it is a peculiarity of entangled quantum states to be delocalized such that they can produce the correlated polarization measurements at space-like separation, we should note that our present considerations about ICCs do not hinge on this quantum non-locality in any way (causal graphs and statistics do not involve spatio-temporal features).

3.3 All proposed quantum ICCs are due to quantum entanglement

Despite the differences between the four classes of ICCs, there is a common feature (which at first sight might seem unintuitive): All mentioned processes defining a class are in fact cases of quantum entanglement. The reason is simple: According to the quantum mechanical formalism, if there are two alternative scenarios, say, x_0 and y_0 happening with a certain probability q, and x_1 and y_1 occurring with probability $1-q$ (as in our paradigmatic scheme for an ICC), then the *only* way of the quantum mechanical formalism to express this is exactly to ascribe an entangled state as in (5).

Prior to its decay, Cartwright's molecule is in the state (5), where the momentum states of the one particle ($|x_0\rangle$, $|x_1\rangle$) are entangled with that of the other ($|y_0\rangle$, $|y_1\rangle$). Or consider again the case of an excited atom that emits a photon (an excitation of the mode of the electromagnetic field) and thereby transits to its ground state: Since atomic states are always coupled to the electromagnetic field, the excited state is, in fact, an entangled state of an atom's excitation state and the excitation state of a mode of the electro-magnetic field, which eventually transits to a product state of the two (see Walls and Milburn 2008). While entanglement is usually only associated with its paradigm cases in EPR/B experiments, this consideration points to the fact, which is well-known among physicists, that entanglement is widespread in quantum systems with more than one object.

Consequently, the prima facie categorisation of quantum ICCs into different classes (i)–(iv) is somewhat misleading. In fact, *all classes of proposed quantum ICCs are instances of quantum entanglement.* Hence, *entangled quantum systems are the most serios candidates for genuine ICCs in our world.* This insight allows to narrow down our quest for genuine ICCs: The question whether there are genuine ICCs reduces to the question *whether entangled systems involve genuine ICCs.*

4 Causal analysis of the quantum mechanical formalism

We shall now examine whether entangled systems, which are the most serious candidates for ICCs in our world, are correctly described by an ICC structure. We develop an answer by investigating which causal structure a literal interpretation of the quantum mechanical formalism suggests for entangled systems. We have already said that in this paper we assume a standard collapse interpretation of quantum mechanics.

The quantum mechanical formalism, as we have noted above, describes the present case as follows: The system is described by an entangled state (5) which at a certain point in time collapses (with some probability) into one of two possible product states (6). Which causal structure appropriately represents this formal description? The answer to the question is controversial. I agree with those authors who assume that the entangled state $\boldsymbol{z}$ is an interactive common cause of the states of the disentangled particles $\boldsymbol{x}$ and $\boldsymbol{y}$ after collapse (Figure 3a; van Fraassen 1982a; Cartwright 1989; Butterfield 1989). I shall now defend the view by an analysis of the quantum mechanical formalism in terms of causal modelling.

In developing my answer I shall also discuss rival proposals. Most of the structures that we have introduced in section 2.2 as being able to generate apparent ICCs have alternatively been suggested for modelling entangled systems. Especially I shall discard the widespread view that there is a connection between the effects of the entangled state (the measurement outcomes in EPR/B experiments). I first discuss whether the variables are appropriately chosen before I treat the connections between them.

4.1 Modelling the entangled state prior to collapse

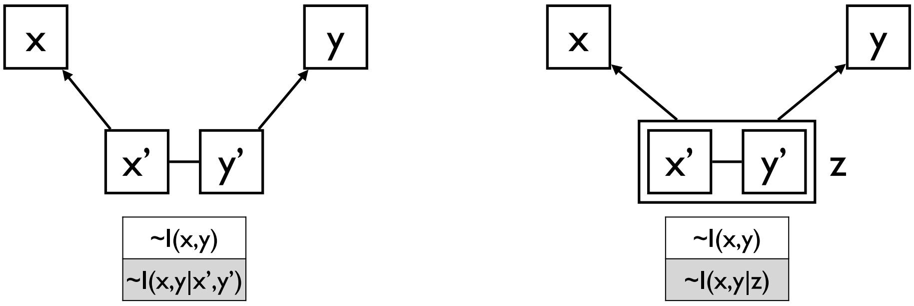
The proposed ICC model describes the entangled quantum state (5) prior to collapse as a single variable $\boldsymbol{z}$ because entangled states are non-separable.

One might object that despite its non-separability the entangled state in the quantum mechanical description is composed of states for each of its two components and also that at measurement the entangled system decays into *two* systems. It might therefore seem natural to assume the entangled system as being composed of two subsystems, each of whose states should be described by the value of a distinct variable and at the same time closely related due to being non-separable. One might wish to symbolize the intimate relation between the two by an undirected edge (resulting in a structure similar to the one shown in Figure 4a). Note that, as $\boldsymbol{x}'$ and $\boldsymbol{y}'$ are supposed do be distinct variables, though connected by a relation of non-separability, each $\boldsymbol{x}'$ and $\boldsymbol{y}'$ can be a cause, i.e. the origin of a an arrow in the graph.

If, in contrast, one thinks that the nonseparable state $\boldsymbol{x}'$–$\boldsymbol{y}'$ should be considered as *one* cause, one is proposing something like the structure in Figure 4b – which means that one is essentially back to describing the entangled state as one variable in the causal diagram (modulo an internal structure, which, as we shall argue in the following, fails anyway). So we leave aside the proposal in Figure 4b and discuss the one in Figure 4a.

Whereas, prima facie, such a structure might seem to capture entanglement in an intuitive manner, there are at least three difficulties. A minor problem is that one would have to make clear, how to derive probabilistic consequences from a structure with the unusual element of an indirected edge (I think that this can be overcome).

Second, since variables in causal modelling must have definite values, each $\boldsymbol{x}'$ and $\boldsymbol{y}'$ would have to have a definite value, i.e. each describes a well-defined state of the



(a) Non-separability 1

(b) Non-separability 2

Figure 4: Proposals for modelling the non-separable entangled state

corresponding component system (and the connection between them just indicates that there are restrictions for the possible combinations of values). This model is incompatible with the ray view of quantum states (see Maudlin 1998), according to which the component states in entangled states are not well-defined. Instead, it is committed to the statistical operator view of quantum states, which does ascribe a well-defined state to the component systems of entangled states (reduced density matrix).

The most severe problem in the present context, however, is that even the complete non-separable state $\boldsymbol{x'}$–$\boldsymbol{y'}$ does not screen off the correlation between $\boldsymbol{x}$ and $\boldsymbol{y}$. So replacing a single variable $\boldsymbol{z}$ by a more fine-grained description $\boldsymbol{x'}$–$\boldsymbol{y'}$ could not help to avoid the entangled state to be a genuine ICC. For this reason and because the model has the mentioned further problems, I shall describe the entangled state prior to collapse by a single variable $\boldsymbol{z}$.

4.2 Are there further relevant variables prior to collapse?

According to the proposed model, the entangled quantum state $\boldsymbol{z}$ is the only variable prior to collapse. Are there further relevant variables prior to collapse that need to be taken into account? The question is relevant because it is well-known that omitting proper common causes can lead to apparent ICCs (Figure 3b–d).[6] Hence, having accounted for all common causes of the set of considered variables is a central requirement in causal modelling ('causal sufficiency').

First, since here we are presupposing that the quantum mechanical formalism is complete, we can safely rule out that there are states beyond the quantum mechanical formalism that need to be considered. This precludes structures that presuppose that the entangled quantum state is an incomplete description requiring a more precise

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[6] Spirtes et al. (2000, 35f) show that Salmon's case of billiard balls is a too coarse grained description of a common cause (Figure 3b) and that Davis' description of a bulky TV switch (1988) omits an intermediate common cause (Figure 3d).

Näger, Paul M. (2021). Evidence for interactive common causes. Resuming the Cartwright-Hausman-Woodward debate. *Preprint.* philsci-archive.pitt.edu/18954/

characterization by hidden variables $\boldsymbol{u}$ (Figure 3b) or that there is a further latent common cause (Figure 3c).

Second, according to the quantum mechanical formalism in many typical cases of entanglement there are further properties or states, which, however, are usually not explicitly taken into account since they either do not change or are irrelevant for the description of the experiment. Take for example an EPR/B experiment with electrons whose spins are entangled. Besides the entangled spin state, the photons have intrinsic properties like mass, charge or total spin which, however, do not change over the experiment.

Furthermore, besides the entangled state, the quantum state of the electrons comprises a wave function component, which describes the motion of the electrons to the detectors. This might suggest to represent the state of the electrons by a second variable. However, the wave function component does not play any relevant role for the interesting part of the experiment, the non-local collapse presumably involving an ICC, and in particular, it would not make the entangled state screen off. For this reason it has become usual to only consider the entangled spin component and to neglect the wave function component.

Finally, we should emphasize that according to the quantum mechanical description, there is no intermediate common cause $\boldsymbol{u}$ (as in Figure 3d) that screens off. The entangled quantum state is the last state before collapse and the transition from the entanlged state $\boldsymbol{z}$ to the collapsed states $\boldsymbol{x}$ and $\boldsymbol{y}$ is temporally not extended: The entangled system described by $\boldsymbol{z}$ exists up to the very point in time at which the separate objects described by the product state start to exist. Especially, there is no instance in time at which an intermediate state $\boldsymbol{u}$ might exist.

4.3 The product state after collapse is not a unit

The state immediately after collapse of the entangled state is a product state and reads $|x_0\rangle \otimes |y_0\rangle$ or $|x_1\rangle \otimes |y_1\rangle$, respectively, where the sign '$\otimes$' denotes the tensor product. (In short notation one often omits the sign, cf. e.g. (6)). While we have seen that the entangled state is plausibly modelled as one variable, the product state lacks all the peculiar features that make the entangled state so special. There are four essential differences that speak for the case that one should model a product state by the two distinct variables $\boldsymbol{x}$ and $\boldsymbol{y}$ that describe its components.

First, the product state assigns *definite* states to each component system (according to both central interpretations of quantum states).[7] The two states connected by the tensor product (in a two-particle product state) are definite (one-particle) states, each describing one of the objects that have been disentangled by the collapse. That the values of the component variables are well-defined is a necessary requirement for regarding them as variables of a causal model.

Second, the component states of product states are *synchronically separable*. Describing the state of the one object by $|x_0\rangle$ or $|x_1\rangle$, respectively, is a complete description of its state (at a certain instant). There is no need to refer to the state of the other object.

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[7] Ray view or statistical operator view, respectively.

There is no connection between the components of product states. Joining states by the tensor product is quantum mechanics' rule to form the joint state of two (or more) separate systems. Any correlation between the components of such systems must be due to their common causal history.

Third, the joint product state supervenes on the component states and it is therefore the latter which should be regarded as *fundamental*. There is no further variable besides the product state that describes the joint system. Consequently, describing the joint system by one variable would describe a non-fundamental level and therefore not fit well with the structure of the quantum mechanical description.

Fourth, the component states of product states are *diachronically separable* if the objects do not interact: In this case one can separate the dynamical equations for each component system (in quantum mechanics: Schrödinger equation) and treat them independently. Without interactions, there is no connection between the component states of product states.

In sum, the component states of quantum product states are as separate and distinct as are states in classical physics (whose joint state is described by a Cartesian product state). Quantum theory, which is our best theory of entangled systems including their dynamics, describes the systems after collapse by two distinct variables, and there is no evidence in its description for counting them as one joint variable. For these reasons, the proposed model describes the state of each subsystem as values of distinct variables $\boldsymbol{x}$ or $\boldsymbol{y}$, respectively.

Against this direct, literal reading of the quantum mechanical description one might object that there are features of the product state after collapse that speak for the case that $\boldsymbol{x}$ and $\boldsymbol{y}$ in fact are not separate and distinct and therefore should be described as one variable. Three options have some prima facie plausibility: (i) $\boldsymbol{x}$ and $\boldsymbol{y}$ denote the *same* event by different descriptions (Figure 3h, unit by identity) or (ii) $\boldsymbol{x}$ and $\boldsymbol{y}$ describe *different parts of one* event (Figure 3i, unit by composition) or (iii) $\boldsymbol{x}$ and $\boldsymbol{y}$ are *not independently fixable* (for some other reason than identity; Figure 3j, unit by dependent fixability). In each of these cases, if one wrongly considers $\boldsymbol{x}$ and $\boldsymbol{y}$ as two different events, their cause *appears* to be an interactive common cause. Note that, when talking about entanglement in EPR experiments in the following, the states after collapse $\boldsymbol{x}$ and $\boldsymbol{y}$ are also called 'measurement outcomes' or simply 'outcomes'.

4.3.1 Against unit by identity

An example for the proposal that $\boldsymbol{x}$ and $\boldsymbol{y}$ denote the same event would be the case that z_1 describes the decay of a radium atom, $\boldsymbol{x}$ describes whether an α-particle is emitted, and $\boldsymbol{y}$ whether a helium-nucleus is emitted. Clearly, $\boldsymbol{x}$ and $\boldsymbol{y}$ are identical and therefore perfectly correlated; it is clear that in such situations the same formal scheme as in Cartwright's example holds, hence z_1 *appears* to be an ICC.

The descriptions referring to the same event need not be analytically equivalent as in the given example; it suffices that they non-analytically refer to the same event (as for Frege's morning and evening star). As in any such case $\boldsymbol{x}$ and $\boldsymbol{y}$, represented as distinct variables, would violate the requirement that variables in a causal graph must describe distinct states, I suggest to represent such situations by including both $\boldsymbol{x}$ and $\boldsymbol{y}$ in one node and indicating the identity of their referent by an identity sign (figure 3h). Then the correlation internal to the node is explained by the identity of the variables, and there is no external correlation between distinct variables that could violate the CMC.

There is, however, no question that this proposal cannot be true in the case of entanglement. For it would amount to saying that one electron turning out spin up is the very same event as the other electron turning out spin down. A claim of identity in this case would contradict the uncontroversial facts that, first, there are *two* electrons, and, second, that the electrons (in the present example and generally) differ in their properties. So strict event identity is out of question in this case.

4.3.2 Against unit by composition

The idea that $\boldsymbol{x}$ and $\boldsymbol{y}$ should be described as one event because they describe different parts of an event that should be considered as a unit amounts to the claim that the ICC is apparent due to a mereological misdescription. As an instructive example one can consider the case of a radium atom emitting an α-particle, consisting of two protons and two neutrons, with a certain probability lower than 1.[8] If by z_1 one describes the decay event, by $\boldsymbol{x}$, whether two protons are emitted, and by $\boldsymbol{y}$, whether two neutrons are emitted, we again get the same formal situation as in Cartwright's example (1).

This model, however, misdescribes the situation, since the α-particle is *one* object, so its emission should not be described by two different variables. Rather one should represent $\boldsymbol{x}$ and $\boldsymbol{y}$ as *one* node in the graph (figure 3j), i.e. $\boldsymbol{z}$ is not a common cause but a usual single cause. In this example ontological—more precisely: mereological—considerations play a crucial role: It is the unity of the α-particle which requires to summarize $\boldsymbol{x}$ and $\boldsymbol{y}$ as one variable and leads to accept the correlation between the variables as not in need of causal explanation.

One might be tempted to advance a similar claim for entangled systems: Rather than describing each component of the product state after collapse separately, e.g. one electron having spin up and the other having spin down, one might think that these states compose a joint state that must be described as a unit. Then, $\boldsymbol{x}$ and $\boldsymbol{y}$ should not be considered as separate variables but as a composite variable $\boldsymbol{xy}$. According to this re-description there simply would be no correlation between distinct variables that needs to be explained, hence the CMC could not be violated.

In contrast to the case of the α-particle, however, I deny that the description of the product state after collapse as a causal unit is correct because there is no criterion according to which a quantum mechanical product state should be regarded to be a unit. First, it is clear that entanglement cannot help to lay the foundations of a unit in this case since the emerging objects after collapse are not entangled any more.

Second, our examples of entangled systems show that the objects emerging after collapse are not generally bound to each other (e.g. Cartwright's molecule or an atom

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[8] This example is due to Hausman and Woodward (1999, 551) and is intended by the authors as a misdescription by dependent fixability (see below), but one can also read it as a mereological misdescription.

emitting a photon).[9] (In the case of the α-particle this criterion is fulfilled, since the α-particle consists of two protons and two neutrons binding with each other.)

Third, the sub-states of the product state, i.e. the cadidates for the parts of the composite state, can be arbitrarily spatially separated: In typical setups of EPR experiments, the states after collapse describe objects that are non-locally related without borders. (The components of the α-particle, in contrast, are close to each other.)

Fourth, to adduce that the two events form a unit because they are subject to conservation laws does not seem a reliable criterion of composition. It is true that in cases of decay the two states complement each other such that, for instance, if the one is spin up the other must be spin down – and vice versa. Knowing the one lets one infer the other. The possibility of inference, however, does not seem to licence the conclusion that the two are parts of *one* event. Compare: If, after collision, one billiard ball rests one can infer that the other rolls, but one surely would not assume that the ball resting is part of one event that comprises the other ball rolling.

In sum, there is no evidence to describe the product state after collapse as a unit due to composition.

4.3.3 Against unit by dependent fixability

Woodward's position

A third possibility of producing an apparent ICC has been discussed by Hausman and Woodward (1999): $\boldsymbol{x}$ and $\boldsymbol{y}$ are not sufficiently distinct to be separate variables in causal models, but should rather be described as one variable. The criterion for distinctness of variables Hausman and Woodward appeal to is today widely called 'independent fixability' (IF; 'independent disruptability' in their paper from 1999) and is a central and necessary requirement for (purely) causal models according to an interventionist theory of causation: The set of variables in a causal model has to be chosen such that 'it is possible to intervene on every variable [. . .] and to set each such variable to each of its values independently of the values to which other variables are set.' (Woodward 2015, 312) If a set of variables contains a pair of variables that cannot be intervened on independently, the set is not suited to serve as the basis for a (purely) causal model.[10]

Hausman and Woodward illustrate their idea with the case of a radium atom emitting an α-particle (that we have already presented in Section 4.3.2). They caution that one should not choose one variable $\boldsymbol{x}$ to describe whether two protons are emitted, and another $\boldsymbol{y}$ to describe whether two neutrons are emitted, because that would violate independent fixability: One could not intervene on $\boldsymbol{x}$ without intervening at the same time on $\boldsymbol{y}$ (and vice versa). In other words, one cannot break the causal mechanism from $\boldsymbol{z}$ to $\boldsymbol{x}$ without breaking the one from $\boldsymbol{z}$ to $\boldsymbol{y}$ (and vice versa). Accordingly, they claim

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[9] For bonding as a criterion of composition see Husmann and Näger 2018.

[10] Woodward (2015) acknowledges that there might be models violating IF because there are non-causal dependences between the variables in question, such as logical relations, supervenience relations etc. We shall discuss the question of possible connections between separate outcomes in Section 4.5. In the present section we follow Hausman and Woodward's idea that IF must be restored by regarding the measurement outcomes as one variable.

that the emission should be described by *one* variable, i.e. $\boldsymbol{x}$ and $\boldsymbol{y}$ are represented as *one* node in the graph (figure 3j), i.e. $\boldsymbol{z}$ is not a common cause but a usual single cause.

Now, for entangled systems Hausman and Woodward (1999, 564–7)[11] advance a similar claim: They maintain that the state after collapse, i.e. the product state, which consists of the two measurement results $\boldsymbol{x}$ and $\boldsymbol{y}$ should in fact be described as one variable, avoiding $\boldsymbol{z}$ to be an ICC, because independent fixability fails for $\boldsymbol{x}$ and $\boldsymbol{y}$:

> The notion of an intervention with respect to one of the measurement events is not well-defined in the EPR phenomena, because the distinction between intervening with respect to [$\boldsymbol{x}$] and acting directly on both [$\boldsymbol{x}$] and [$\boldsymbol{y}$] cannot be drawn. The reason given for this within the standard interpretation is that the correlated particles are in a so-called non-separable or entangled state. In some way that is difficult to understand, the two particles constitute a single composite object, even though they may be at spacelike separation from each other. The measurement result on one wing [of an EPR/B experiment] is not really a distinct event from the result on the other wing but rather both comprise 'a single, indivisible non-local event' (Skyrms [1984], p. 255).
>
> (Hausman and Woodward 1999, 566)

The central idea here is that the measurement outcomes $\boldsymbol{x}$ and $\boldsymbol{y}$ should not be considered as distinct causal variables since they are not independently fixable.[12] This would amount to saying that one may not consider one electron having spin up ($\boldsymbol{x}$) as a distinct event from the other having spin down ($\boldsymbol{y}$), but needs to consider the two as one *joint* event $\boldsymbol{xy}$. According to this re-description there simply would be no correlation between distinct variables that needs to be explained, hence the CMC could not be violated.

Different readings

The truth of the claim that the measurement outcomes are not independently fixable crucially depends on what exactly one means by 'measurement outcomes'. I shall now discern three different readings only one of which makes the claim true. Subsequently,

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[11] On these pages, Hausman and Woodward defend in fact two different but similar views by similar arguments. The view we discuss here seems to be Woodward's (see Hausman and Woodward 1999, fn. 26 on p. 565); we shall examine Hausman's view in Section 4.5.

[12] This is how I read Hausman's and Woodward's claim, but the presentation is not without ambiguouity: The reason they give for the failure of independent fixability, that the particles are in a non-separable state, might, in contrast, suggest that their view just is that one cannot act on one particle without acting on the other *as long as the two are entangled*. If this were the case, the claim would be uncontroversial: I have already agreed above to describe the entangled state as one variable $\boldsymbol{z}$. It would, however, be uninteresting for the question whether an ICC exists, because that essentially requires to model the collapsed state as well.
Since, however, Hausman and Woodwared speak about the measurement outcomes $\boldsymbol{x}$ and $\boldsymbol{y}$, which are clearly not entangled and hence separable, and since their argument is meant to exclude an ICC, I think that their claim must be interpreted to be about the *collapsed product state* (or some effects of it, to be discerned below); consequently, I take their note about non-separability to refer to the entangled state *prior* to the measurement outcomes.

I shall explain why even in the reading according to which the assumption of distinct variables would violate IF there are good reasons to regard the variables to be distinct.

In order to be able to discern different possible readings, let us make clear the measurement process according to a standard collapse interpretation of quantum mechanics: We have a system of two particles, say two electrons, in an entangled state, which above I have argued to be appropriately described by one variable $\boldsymbol{z}$. Each particle moves towards a measurement device[13] and at the point in time t_1, when the first particle, say the left one, hits the detector, the entangled state collapses instantaneously to a product state, described by quantum mechanics as $|x_0\rangle|y_0\rangle$ or $|x_1\rangle|y_1\rangle$. From this moment on the dynamical evolution of the two particles is decoupled: the first particle further interacts with the matter of the detector (either it is scattered or absorbed), however, since the particles are disentangled, without affecting the second particle, which is still on its flight to the other detector. In the physical description of such experiments one is not interested in the states of a particle after it has hit the detector; rather what is important is that the interaction changes the physical state of the detector such that the detector outputs a signal that is transferred to a humanly readable display; say, the left measurement result is displayed starting from t_2. When the right particle hits the detector (say at $t_3 > t_2$), it interacts with the detector, which starts a process that causes the right display of the measurement result starting at t_4.

This somewhat detailed description will now help us to discern different readings of Hausman's and Woodward's claim. Let us call the immediate states of the electrons after collapse (at t_1) $\boldsymbol{x}$ and $\boldsymbol{y}$, the non-immediate states of the electrons after collapse $\boldsymbol{x}'$ and $\boldsymbol{y}'$ (at some $t > t_1$) and the displays of the measurement devices $\boldsymbol{x}''$ (at t_2) and $\boldsymbol{y}''$ (at t_4). Any of these pairs of variables might with some reason be called 'measurement outcomes' and Hausman and Woodward do not say explicitly which of these events they mean when they claim that the measurement outcomes are not independently fixable — so let us assess their claim for all three possible meanings.

First, in the debate about EPR experiments and entanglement 'the measurement outcomes' usually denote the displays of the measurement devices $\boldsymbol{x}''$ and $\boldsymbol{y}''$. Understood in this way, it would be false to claim that the measurement outcomes are not independently fixable: One can clearly fix the display of the measurement device $\boldsymbol{x}''$ by some intervention, e.g. one can intervene on the position of the displaying pointer just as one can intervene on a barometer dial (the latter is one of Hausman and Woodward's example of a valid intervention, see their 1999, p. 536).

Second, also the non-immediate states $\boldsymbol{x}'$ or $\boldsymbol{y}'$ of the electrons after collapse are independently fixable. Since at the time of the non-immediate states the intimate connection due to entanglement has ceased to exist the process from $\boldsymbol{x}$ to $\boldsymbol{x}'$ is independently disruptable from the process from $\boldsymbol{y}$ to $\boldsymbol{y}'$; and since the time interval between the collapse and the non-imediate states is finite, there is no principled obstacle to perform an intervention. Intervening on the spin of the one electron ($\boldsymbol{y}'$), is possible and would

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[13] Each measurement device has a certain setting for the measurement direction, but the settings are irrelevant for the questions discussed here and would only complicate matters, so we assume that they are constant in each run such that we can ignore them here.

not change the spin of the other ($\boldsymbol{x}'$). Consider, for instance, the state $\boldsymbol{y}'$ of the electron that is still on its way to the right detector: One can perform all sorts of local physical manipulations on the state of this particle (e.g. reversing the spin by magnetic fields) that will not affect the other particle (since the particles are disentangled since t_1) and that, if suitable, fix the value of the variable.[14]

Third, concerning the immediates states $\boldsymbol{x}$ and $\boldsymbol{y}$ after collapse (at t_1), however, the claim that independent fixability fails is true. One cannot intervene on $\boldsymbol{x}$ (by disrupting the process to $\boldsymbol{x}$) without disturbing $\boldsymbol{y}$ because the processes leading from $\boldsymbol{z}$ to $\boldsymbol{x}$ and from $\boldsymbol{z}$ to $\boldsymbol{y}$ are both described by the collapse. There is no way to interrupt the collapse for one variable but not for the other. (The reason for the failure of IF is emphatically not that $\boldsymbol{x}$ and $\boldsymbol{y}$ are non-separable – forming a product state they are separable!) Consequently, the best reading of Hausman's and Woodward's claim that the measurement outcomes are not independently fixable is that it is *the immediate states of the quantum objects after collapse*, described as two distinct variables, which are not independently fixable.

Objections

What should one conclude from the failure of independent fixability for the immediate states after collapse when described as two variables? There are two rough options. First, assuming independent fixability as a necessary criterion for variables in causal models to be distinct (as Hausman and Woodward and other proponents of interventionist theories of causation do) implies that the immediate states after collapse must be described as *one* variable. In this redescription there would be no question of a failure of independent fixability, because there are not two distinct variables. Also the CMC holds because the problematic correlation between the outcomes is hidden in the joint variable. The move to describe the immediate effects of collapse as one variable makes the model in accordance with usual principles of causal modelling.

In contrast, second, to describe the immediate states after collapse as two distinct variables would make the resulting model violate independent fixability as well as modularity and hence would constitute an anomaly for interventionist theories of causation that require the assumptions. The CMC is *not per se* violated in this case, which prevents the description by two distinct variables being per se an anomaly for the theory of causal Bayes nets. Whether the CMC in fact is violated depends on the question if there is a connection between the two variables (CMC holds, no ICC) or not (CMC fails, ICC

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[14] It is physically more challenging to intervene on the state $\boldsymbol{x}'$ of the other particle that has already interacted with the detector. We have said above, that this state does not play any role in the physical description of EPR measurements, since the particle has already 'done its job' in interacting with the detector, so this state is not included in the standard quantum mechanical description of the experiments. I am not claiming here that one can even intervene on this state in all cases; there might be physical obstacles to interventions (which would be a problem for interventionism), e.g. because the particle is located inside a piece of solid matter (the detector). What I am rather claiming here is twofold: If it can be intervened on (e.g. after it has been scatterd by the detector) the intervention would not affect the state of the other particle (since the particles are disentangled); and if it cannot be intervened on because it has been absorbed and ceased to exist (as usual in the case of photons), one cannot intervene on it, but then independence to the other process holds trivially.

exists). We shall discuss this question in Section 4.5 (and argue against the CMC that there is no connection and an ICC exists).

In short, when asked to describe the immediate states after collapse as one or two variables the choice is between upholding a central assumption of interventionism, independent fixability, or stating its failure because a description by two variables is more appropriate. Opting for a description with two variables would constitute a causal anomaly in the sense of violating a usual principle of causal modeling. While it is clear that it would be desirable to uphold all usual principles of causal modelling, I think that there are at least three good reasons to describe the immediate states after collapse as two distinct variables and to accept the causal anomaly in such cases.

First, I have argued above that according to quantum mechanics the states immediately after collapse are described by two separate variables. So our best scientific theory of such systems makes a clear choice, and I think it is reasonable to require that causal models should be in accordance with our best scientific theories. One might object that quantum theory should not be taken too seriously when it comes to judging matters of causation because it is not based on the principles of causal modelling. That, however, seems a questionable assessment. Quantum theory does provide information that is relevant for causal models: It is an essential part of the quantum theoretical description (i) how to segment systems into distinct variables and (ii) how these variables evolve dynamically over time, especially which variable influences which — and this is exactly the information that is summarized in causal models. Quantum mechanics provides well-tested and the best description of this kind for entangled systems that we have.

Similarly, second, causal models should agree with our best ontological models. I have argued above that there is no reasonable criterion of composition that would require to regard the variables as one. According to all criteria the variables should be considered to be distinct. Then, to assume the immediate states after collapse as one variable would be in tension with our ontological assessments.

Third, describing the immediate states after collapse as one variable would have the consequence that the deep and mysterious EPR/B correlations would not require explanation any more since the first occurrence of the correlation is hidden *inside* the joint variable. It is, however, difficult to believe, that the notorious EPR correlations should turn out as a mere artefact of misdescription, a *scheinproblem* in the modern philosophy of physics. While one can challenge that the EPR correlations can be explained causally (although I think they can), causal models should definitely not hide them, but rather make them explicit. To describe the case with two variables would just do that: make the anomaly explicit.

In sum, I think that the reasons for describing the immediate states after collapse as two separate variables are quite strong such that the resulting violation of independent fixability is well-founded.

The violation of IF appealed to here does not seem to be restricted to the quantum realm. As an illustration, imagine the case of dividing a piece of twine in two halves with scissors. Let $\boldsymbol{z}$ describe the position of the scissor relative to the undivided twine before the cut and $\boldsymbol{x}$ and $\boldsymbol{y}$ denote the length of the left and right piece of twine, respectively, immediately after division. Clearly, the processes towards $\boldsymbol{x}$ and $\boldsymbol{y}$ are not independently disruptable: One cannot interrupt the process to the one without interrupting the process to the other. This does not imply, however, that $\boldsymbol{x}$ and $\boldsymbol{y}$ are not separate variables. Then, IF and modularity fail for the twine as for entangled systems.

Since a failure of IF might seem to threaten interventionism as we know it, I recall what I have said in the introduction: My aim here is just to argue that entangled quantum systems involve some kind of causal anomaly, violating central principles of causal modelling (here: IF and modularity), and I am silent about what this implies for causal modelling. It is clear that without further argument a failure of IF does *not* imply that interventionism is wrong (and therefore needs to be revised or given up): A supporter of interventionism can uphold her theory by claiming that entangled quantum systems are acausal and should not be modelled causally.

As a result of the considerations about the quantum mechanical formalism so far, we note that the quantum mechanical description of entangled states should be understood to involve three distinct variables $\boldsymbol{z}$, $\boldsymbol{x}$ and $\boldsymbol{y}$. We now turn to the question which connections hold between these distinct variables.

4.4 The entangled state is a common cause of the collapsed states

The proposed model involves a causal relation from $\boldsymbol{z}$ to $\boldsymbol{x}$ and from $\boldsymbol{z}$ to $\boldsymbol{y}$, such that $\boldsymbol{z}$ is a common cause of $\boldsymbol{x}$ and $\boldsymbol{y}$.

It is natural to think that the entangled state is a cause of its collapsed state, and none of the usual models denies this. To justify the claim, the causal relations in questions can be inferred by interventions. Interventions on the entangled quantum state are in most cases unproblematic since in typical EPR/B experiments the experimenter prepares, and hence controls the quantum state. There is no evidence that the preparation of the entangled state might not be an intervention.An experimenter can vary the entangled stated at will (e.g. vary the value of q in (5)) and then observes that under such interventions on $\boldsymbol{z}$, $\boldsymbol{z}$ is correlated with $\boldsymbol{x}$ as well as with $\boldsymbol{y}$. Hence, by usual standards of causation $\boldsymbol{z}$ is common cause of $\boldsymbol{x}$ and $\boldsymbol{y}$.

4.5 There is no connection between the collapsed states

The proposed model assumes that there is no direct connection between the collapsed states $\boldsymbol{x}$ and $\boldsymbol{y}$. If this is true the CMC is definitely violated, because even conditional on the common cause $\boldsymbol{z}$, $\boldsymbol{x}$ and $\boldsymbol{y}$ remain correlated to some degree – and this 'excess correlation' that is not screened off by $\boldsymbol{z}$ cannot be explained by the CMC.

It is clear that conservatives about causal modelling, who acknowledge that the outcomes are separate variables (as we have argued above), have a high motivation to assume a model according to which there is a connection of some kind between $\boldsymbol{x}$ and $\boldsymbol{y}$ that might explain the failure of screening off in a way consistent with the CMC. The connection might be either causal in one direction (Figure 3e) or bidirectionally causal (which would be a loop of two causal processes in opposite direction; Figure 3f), or symmetrically non-causal (here depicted as a non-directed edge, Figure 3g).[15]

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[15] It is even conceivable to assume an asymmetrical non-causal connection. Since, however, nobody

Most proponents of a connection between the outcomes have assumed the connection to be non-causal because causation has been associated with a flow of conserved quantities and the ability to send signals, but it is well-known that there is neither a flow of conserved quantities from one wing of an EPR experiment to the other, nor can one send signals (and furthermore both seems to be forbidden between space-like separated events by the principles of relativity). The abstract approach to causation assumed by causal modelling, however, is not committed to such characterizations of causation, and, in fact, a recent analysis has revealed that quantum mechanics explains the failure to send signals by a fine-funing of the causal parameters (Näger 2016). So although the majority view is on the non-causal side, we here do not rule out causal relations from the start and generally discuss the evidences for a connection, whether causal or non-causal (it will turn out that the arguments against a connection are general in this respect). What is important is that we need to look for a *real physical* connection; a mere correlation and any epistemic relation that is implied by mere correlations like 'knowing A entails B' would not suffice (correlations are the explanandum, not the explanans).

There is one difference, though: While models with a causal relation would save the CMC, models involving a non-causal relation would literally violate the CMC. However, Gebharter and Retzlaff (2020) explain that – in contrast to models without any connection – the main idea of the causal Markov condition (and Bayes net modelling), that correlations are to be explained by structure, can be saved in such scenarios when one generalizes the CMC to structures including non-causal relations ('global Markov condition', GMC). If the GMC is correct, it solves the additional challenge for the view of acausal connections, namely to provide a rule for how to derive probabilistic consequences from a structure with the unusual element of a symmetric non-causal relation (compare a similar problem for the proposal in Section 4.1).

4.5.1 Hausman's view

Hausman and Woodward (1999) are among the proponents of a non-causal connection between the outcomes. They present the position (which seems to be Hausman's view) as an alternative to their view that assumed the unity of $\boldsymbol{x}$ and $\boldsymbol{y}$ (which is Woodward's position; see our discussion in Section 4.3.3 and especially Footnote 11):

> [The measurement results of EPR/B experiments] are distinct events, but they are not probabilistically dependent on one another in virtue of being cause and effect or effects of a common cause. Instead they bear a different kind of non-causal (but non-accidental) relation to one another. (Hausman and Woodward 1999, 564f.)

Since they advance this claim in the context of a discussion of common cause models $\boldsymbol{x} \leftarrow \boldsymbol{z} \rightarrow \boldsymbol{y}$, it seems fair to assume that they do not mean that there is no common cause at all, but rather that the correlation between the measurement results are *not only* in virtue of a direct causal relation or common cause, as the common cause will

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seems to have taken this view, we omit it here (however, what I say against the related models in the following can easily be applied to this case as well).

surely contribute to the correlation to some extent. If this interpretation is correct, their view might best be represented by a structure similar to Figure 3g.

In order to assess the position one would need more details about the kind of the non-causal relation and evidence why to assume it. Since Hausman and Woodward, however, do not provide these details, we move on to more explicit, elaborated versions of this kind of model (leaving open that they could have meant one or the other of the following models).

4.5.2 Making the models more explicit

The view that there is a non-causal, correlation producing, or at least correlation explaining, relation between the measurement outcomes is rather widespread in the debate about entanglement and Bell's theorem. The strong correlation between the outcomes that persists even given the complete quantum state at the source ('outcome dependence') has been thought to establish some kind of non-causal connection between the outcomes and has been given different names, most prominently 'passion at-a-distance' (introduced by Shimony 1984 and adopted by others, e.g. Redhead 1986; Jarrett 1989) While the view emerged from the discussion about the more general Bell theorem, in the following we shall examine what we can say from a causal modelling perspective on the basis of the quantum mechanical formalism.

Since the connection is assumed to hold between 'the measurement outcomes', we should recall the discussion from Section 4.3.3 that there are different possible understandings of the term, which might either mean the states of the particles immediately after collapse, or the non-immediate states of the particles after collapse or the humanly readable displays of the measurement apparatuses. Here as well, I think, it is obvious that when the claim about the connection between the outcomes is to make any sense, it should presume the first meaning. So the models we are considering here assume that the states immediately after collapse are connected by a symmetric non-causal relation of some kind.

How could one justify a connection? I emphasize that in the present context it would be question begging to argue that there must be some kind of connection between the outcomes because the CMC (or GMC) requires it in order to explain the strong correlation. Since the question here exactly is whether there are genuine ICC structures violating the CMC, simply assuming that the CMC holds without giving further reasons, would not be acceptable. A proponent of the model needs independent reasons for the existence of a connection.

In principle one could adduce the results of Bells's theorem that there must be some connection between the wings of the experiment and then add further reasons why the connection must be between the outcomes. Since in this paper we presuppose quantum theory in a usual collapse version, however, one needs to be more specific: One needs to discuss whether the specific theory at hand provides evidence for the claim. Then the question is whether one can find evidence in the quantum mechanical formalism that there is a connection between the outcomes $\boldsymbol{x}$ and $\boldsymbol{y}$. Since we have already said above that in general the effects of an ICC are not bound to each other, we here have the more general question whether they are connected at all.

In order to establish a connection between the outcomes we need a correlate in the formalism. There are four prima facie possible candidates: interactions, the relation of non-separability, the collapse, conservation laws.

4.5.3 Interactions

It is well-known that usual interaction potentials (that appear in the Hamiltonian) cannot connect the outcomes. Consider, for instance, that the experiment involves two electrons, which due to their charge would clearly interact electromagnetically with each other. But, first, this is not the general case, one could have particles emerging from an entangled state that do not interact at all, say two photons; and second, even if one has an interaction, such interactions do not propagate faster than the speed of light. So the space-like separated outcomes could not be connected in this way.

4.5.4 Non-separability

One might think that the non-causal relation between the outcomes just is a holistic relation of non-separability. However, while it is clear that the entangled state is non-separable, the view that the *measurement outcomes* are non-separable is implausible: By the quantum mechanical formalism, the measurement outcomes occur *after* collapse, i.e. entanglement has ceased to exist and the post-collapse product state we are about to describe is explicitly separable.[16]

This does not mean that the non-separability would not have a role to play for a possible connection between the outcomes. One can still claim that while the non-causal relation holding between the outcomes is not itself a relation of non-separability, it relates to the preceding non-separability of the entangled state by being the kind of relation that emerges when the non-separability of entanglement breaks down due to the collapse.

4.5.5 Collapse

Another, more serious candidate for a connection between the outcomes is the collapse of the entangled state. Being instantaneous it can in principle connect space-like events. Nevertheless, the collapse does not seem to be appropriately described as an influence from the one outcome to the other for two main reasons.

First, the collapse is an instantaneous process which describes the transition from the entangled state (5), the first stage of the process, to the product state (6), the final stage of the process.[17] It is in this sense, maybe somewhat imprecisely, that we have said that the outcomes are the quantum states immediately *after* collapse. But if the

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[16] Note that this view would furthermore raise the above discussed problem that in a non-separable state the components cannot be ascribed definite values (see Section 4.1).

[17] The process from the entangled state to the product state being instantaneous means that the entangled state exists at each instant in an open time interval $[t_0; t_1[$, and at t_1 the product state starts to exist. There is no finite temporal interval and hence no intermediate state between the first stage and the last stage of the process.

product state is the final stage of the process called ‘collapse’, then the collapse cannot be a connection between the components of the product state, which are the outcomes.

Second, rather than describing a positive, physical connection between the objects, the collapse describes the *breaking* of such a connection: The collapse describes the transition from the entangled state, according to which the distant objects are connected by a relation of non-separability, to the product state, according to which each object has its own separate state. So the collapse for entangled systems describes the collapse of the relation of non-separability, and its result is the absence of that formerly existing connection, described by the separate outcomes. According to the quantum mechanical formalism, the outcomes $\boldsymbol{x}$ and $\boldsymbol{y}$ are just components of a separable product state and there is no connection between the two.

Again the analogy with the case of dividing a piece of twine might help to push intuitions here, the collapse being analoguous to the cut: Before the cut the pieces making up the twine are physically connected, and the cut leads to two unconnected pieces. It would be absurd to say that the cut connects the pieces. The strong correlations between the pieces after the cut (they always add up to the original length) cannot be explained by a connection between them.

I conclude that the collapse is not a suitable correlate in the formalism for grounding a connection between the outcomes. The collapse rather seems to be apporpirately understood as a process from a common cause to its effects (and the effects are not connected, at least not by the collapse).

4.5.6 Conservation laws

It has some prima facie appeal to think that the connection between the outcomes might be given by conservation laws, since the collapse of paradigmatic entangled states like the singlet state

$$|\psi_1\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2} \tag{7}$$

seem to conserve the total spin direction S_z^{AB} (the single spin directions sum to zero before and after measurement).

Gebharter and Retzlaff (2020) have recently formulated a view of this kind in the context of causal modelling. They argue that in cases of purported ICCs and especially in EPR experiments the effects of the common cause are connected by a kind of non-causal dependence that ‘arises due to background assumptions which rule how quantities, properties, or parts are distributed among different objects or places if the common cause occurs.’ (p. 1468f.) They hold that in the EPR case the relevant background assumptions or ‘distribution conditions’ (p. 1479) as they also call them, are conservation laws.

> Pairs of entangled photons can, for example, be produced by splitting a photon beam with a non-linear crystal obeying energy and momentum conservation. So there seem to be laws of nature (i.e., the principles of energy and momentum conservation) ruling how quantities are distributed that are responsible for the fact that [$\boldsymbol{x}$] and [$\boldsymbol{y}$] are dependent conditional on [the entangled state and the polarizer settings]. Gebharter and Retzlaff (2020, p. 1480)

They then rule out causal relations (due to the space-like separation of the outcomes) and conclude that the connection between the outcomes established by the conservation laws is non-causal.

I would like to mention two worries that I have with this proposal. First, the proposal seems to amount to that the conservation law determines how the conserved quantities in question are 'distributed' among the two outcomes, such that the outcomes are correlated. We then have the following dilemma: Either the conserved quantities are literally distributed, as the connection indicates, between the outcomes. Then, however, since the outcomes are space-like separated that would involve some kind of superluminal flow or distribution of conserved quantities, in tension with relativity. It does not help for consistency with relativity to just say that the connection is non-causal when a space-like flow of conserved quantities is involved. Alternatively, the conserved quantities are distributed in the preceding process from the non-local entangled state to the outcomes. Then, however, it would be inappropriate to regard the connection as holding between the outcomes, because the distribution has already occurred when the outcomes emerge.

A second worry is this. On the one hand, it is true that conservation laws play a central role in typical generation processes for entangled states. On the other hand, when talking about the correlations of the measurement outcomes given the entangled state, we are not concerned with the generation but with the *measurement* of entangled states, i.e. the existence of an entangled state is presupposed and the measured correlations between the outcomes need to be explained. There is, however, *no conservation law for measurements*: the non-unitary collapse that occurs at measurement does not preserve probability distributions. By collapsing all terms in the superpositon but one, the probability distribution generally changes. For this reason, typical conservation laws in quantum physics refer to the unitary Hamilton dynamics that can, given certain symmetries, preserve certain quantities. Note that relaxing the condition for conservation by assuming that preserving the probability distribution is too strong, does not help either: It is even true that there is no law describing the conservation of the *expectation values* at spin measurement.

Let me shortly illustrate the claim. Given the singlet state, before the collapse, the probability to measure '↑↑' is $\frac{1}{2}$ (and so is the probability for measuring '↓↓'). However, once the collapse has occurred, the probability of measuring '↑↑' is either 0 or 1 (and similarly for the probability to measure '↓↓'). Furthermore, while the expectation value for the relevant variable, the total spin direction S_z^{AB}, does not change for the singlet state,[18] it does change for other entangled states like $|\psi_2\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)$.[19] So the conservation of the expectation value for the singlet state is not law-like; it is an accidental fact since it seems to be due to the symmetry of the state, i.e. the initial conditions, not due to the symmetry of the dynamics.

In sum, at the measurement of entangled states there are no relevant conservation laws involved that a proponent of a connection between the outcomes could refer to.

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[18] $\langle S_z^{AB}\rangle_{t_0} = 0 = \langle S_z^{AB}\rangle_{t_1}$

[19] $\langle S_z^{AB}\rangle_{t_0} = 0 \neq \langle S_z^{AB}\rangle_{t_1} = \hbar$

4.5.7 Result

All prima facie plausible candidates for a connection between the outcomes in the quantum mechanical formalism have turned out to be inappropriate for justifying a connection. I conclude that there is no connection between the measurement outcomes.

One might wonder then, how the strong correlations between the outcomes can occur when the outcomes are not connected. Does not Bell's theorem show that there must be a non-local connection? Of course there is a non-local connection, namely the non-separability of the entangled state. However, there need not be an additional connection between the outcomes, because the correlations observed between the outcomes are already present in the entangled state. Have a look at (5): All possible combinations of outcomes are already contained in the entangled state and all are perfectly correlated. The collapse then just eliminates all possible combinations of outcomes but one, the emerging product state, which then is strongly correlated. In order to secure the correlation, there neither needs to be a conservation law working at collapse and the collapse does not need to connect the outcomes.

Similarly with the twine: The pieces of twine emerging after the cut do not need to be connected in order to be perfectly correlated (by adding up to the original length). The connected pieces of twine before the cut just continue to exist after they have been separated by the cut, and then it is not magic that afterwards they add up to the original length. (In order to see the analogy to the entangled state more clearly, one might think of the twine as having the disposition to be separable at infinitely many points, resulting in correlated lengths of the pieces.)

5 Conclusion

(1) In sum, the quantum mechanical description yields a causal model according to which the entangled state $\boldsymbol{z}$ is a proper common cause of the distinct and unconnected collapsed states $\boldsymbol{x}$ and $\boldsymbol{y}$. Since according to this model $\boldsymbol{z}$ does not screen off the correlation between its effects, the quantum mechanical formalism incorporates genuine interactive common causes, violating the CMC. If $\boldsymbol{x}$ and $\boldsymbol{y}$ denote the immediate quantum states after collapse, which they often do not as one usually considers them to denote the measurement results at the detectors, the model also violates modularity and IF. The arguments presented here provide detailed evidence for Cartwright's claim that there are genuine ICCs.

There were two main rival proposals to avoid an anomaly by redescribing the models with quantum ICCs: One is to describe the product state immediately after collapse as *one* variable $\boldsymbol{xy}$; the other assumes a connection (of some kind) between the separate variables $\boldsymbol{x}$ and $\boldsymbol{y}$. Against Hausman and Woodward and others I have argued that these suggestions to redescribe ICCs are implausible when one understands the quantum mechanical formalism realistically. Hence, if quantum mechanics is true, there are genuine ICCs.

(2) Rejecting the misdescription thesis argues against a natural reaction of many philosophers of causation that reaches back until when the very first examples were raised

by Salmon and others. As long as ICCs could be redescribed to usual causal models, they are no genuine threat to causal modelling or other usual claims about causation. Only when the the misdescription thesis is well supported, as I have tried to argue here, one has to take them and their unusual properties seriously.

It is worth stressing that the aim of this paper was just to reject the misdescription thesis, and the resulting claim is that there are genuine ICCs; i.e. there is a causal anomaly that has the structure of an ICC. Especially, the aim of the paper was *not* to say how to deal with such genuine ICCs or how to explain the unusual correlations it involves.

(3) I should mention that it is consistent with the results of this paper that one can avoid the existence of ICCs, if one claims that quantum theory is not a realistic description of the micro processes in our world. One might assume that there are hidden variables $\boldsymbol{u}$ that characterize quantum systems more precisely than the entangled quantum state $\boldsymbol{z}$ does, yielding one of the structures in Figure 3b–c. The de Broglie–Bohm theory is the most prominent example for such a theory; since its dynamics is deterministic, all common causes trivially screen off.

(4) Once the redescription of ICCs is implausible and their existence is substantiated, further questions about ICCs (see Q2–Q6 above) come into focus, on which I could not touch upon in this paper. Most importantly, we have seen that systems with ICCs violate usual principles of causal modelling: by definition the CMC as well as modularity and independent fixability do not hold in such systems. While a violation of the CMC directly hits modelling by causal Bayes nets, a violation of IF and modularity threatens interventionist theories of causation as defended by Woodward.

There are two main strategies to defend causal modelling against the challenge of ICCs: Either one can assume that entangled quantum systems are not causal (van Fraassen 1982a) and therefore the principles cannot meaningfully be applied (and hence not be violated in a relevant sense). Or, if one considers entangled quantum systems to require causal explanations, systems with ICCs are a counterexample to the mentioned principles, which then need to be revised (for a proposal see Näger 2014; Schurz 2017). Both options are live. Whether one chooses the one or the other, it is clear that once the existence of ICCs is established by suitable evidence, as I have argued here, it has substantive consequences.

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