Superdeterminism: a Reappraisal

SUBMITTED VERSION

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Superdeterminism: a Reappraisal

Abstract. This paper addresses a particular interpretation of quantum mechanics, i.e. superdeterminism. In short, superdeterminism i) takes the world to be fundamentally deterministic, ii) postulates hidden variables, and iii) contra Bell, saves locality at the cost of violating the principle of statistical independence. Superdeterminism currently enjoys little support in the physics and philosophy communities. Many take it to posit the ubiquitous occurrence of hard-to-digest conspiratorial and coincidental events; others object that violating the principle of statistical independence implies the death of the scientific methodology. In this paper, we offer a defense to these and other objections. To counter the conspiracy objection, we draw upon the philosophical literature on time travel, and conclude that the picture of the world offered by the superdeterminist does not need to be particularly surprising or conspiratorial. We then move on to other recent objections, in particular those that focus on the methodology of science and the nature of the physical laws compatible with superdeterminism. A key ingredient of our arguments is that the principle of statistical independence may be violated *in theory*, but valid *for practical purposes*. Our overarching goal is to offer a defense of superdeterminism with respect to its main objections, so that it can earn its keep as a legitimate contender among the possible interpretations of quantum mechanics.

Keywords: quantum mechanics, superdeterminism, Bell's theorem, statistical independence, counterfactuals, coincidences, time travel

Word count: 9960 (excluding abstract)

1. Introduction.

Superdeterminism is one of the possible interpretations of quantum mechanics, one that takes the world to be deterministic and postulates the existence of hidden variables to explain quantum phenomena. In such a view, the Schrödinger equation is taken to be incomplete, viz. as not representing fully how reality is. Furthermore, a superdeterministic theory violates the principle of statistical independence between the hidden variables and the measurement settings: this can be considered the defining feature of superdeterministic theories (a feature made precise in equation (2) below). On the other hand, superdeterministic theories respect the principle of locality, roughly, the idea that causation is continuous in space-time and our universe does not feature "spooky actions at a distance." The superdeterminist's strategy emerged as a response to Bell's theorem. Whereas many take Bell's theorem to conclusively show that nature is non-local, superdeterminists counter this conclusion and argue that there are ways to resist Bell's conclusion and consequently save locality.

Superdeterminism enjoys little support in the physics and philosophy communities. Despite a number of exceptions (e.g. Brans 1988, Lewis 2006, Nieuwenhuizen 2011, [omitted], [omitted], Hossenfelder 2014, Hossenfelder and Palmer 2020, Elze 2020, Donadi and Hossenfelder 2021) including a Nobel laureate ('t Hooft 2014, 2016, 2021), most people consider superdeterminism a non-starter in the debate about the interpretation of quantum mechanics. Indeed, some compelling objections have been raised against it. To start, superdeterminism is criticized because it allegedly requires us to relinquish a standard metaphysical and epistemic principle, viz. the principle of statistical independence. This is taken by some to have disastrous consequences, such as the impossibility of conducting proper science (Shimony et al. 1976, Maudlin 2019, Chen 2021, Baas and Le Bihan 2021). Furthermore, superdeterminism is often dismissed as a "conspiracy theory", since, so goes the objection, its truth requires nature to conspire to make it the case that our empirical evidence matches the predictions of the theory (Shimony et al. 1976). More recently, Baas and Le Bihan (2021) argue that superdeterminism requires a suspicious fine-tuning of the initial condition of the universe, which in turn makes superdeterminism compatible with *only one* metaphysical account of the laws of nature, viz. the Humean account.

The overarching goal of this paper is to argue that superdeterminism cannot be so easily dismissed and that, on the contrary, it deserves the role of a legitimate contender within the debate on the interpretation of quantum mechanics. To achieve this goal, in this paper we intend to illustrate how the superdeterminist has plausible answers to the charges we mentioned in the previous paragraph. In what follows we first recap Bell's theorem and the superdeterminist's response to it (section 2). Next we respond to the objection that presents superdeterminism as a conspiracy theory (section 3). One aim of this paper is to press philosophers to have a closer look at the notoriously controversial concept of "conspiracy" in the context of superdeterminism. Such closer scrutiny has not yet been done in this context; we offer here one entry into this matter. To counter the objection of the alleged conspiratorial nature of superdeterminism, we will draw upon a different body of literature, viz. the philosophical literature on time travel and counterfactuals of coincidence. The metaphysical possibility of time travel raises worries with respect to coincidental events that seem to be bound to happen if time travel were possible (see, among others, Smith 1997 and Dowe 2003). To some, nature should "conspire" to make unlikely coincidences happen. We will use this literature to draw a moral on the alleged conspiratorial nature of superdeterminism, and suggest that there are no conclusive grounds to dismiss the metaphysical and physical picture of the world provided by superdeterminism as conspiratorial. Then we move on to the argument from the laws of nature (section 4). Finally, we address the objections from the impossibility of science (section 5). The main new idea we wish to introduce in the last sections is that, while superdeterminism does indeed violate the principle of statistical independence, this may be harmless after all, in a well-defined sense. Indeed, it is conceivable that ubiquitous statistical dependence exists as a matter of principle, as would be reflected in a – surely elusive – "Theory of Everything" that describes the Big Bang and every event afterwards, while it is often negligible in practice. We will show in detail (section 5) how this allows to respond to a challenge posed by Chen (2021), i.e. how "it is logically consistent for one to claim that statistical independence is false about microscopic systems but for all practical purposes true of macroscopic systems". We will note that our conclusions align with first approximate superdeterministic theories very recently proposed by physicists (notably 't Hooft 2021, Donadi and Hossenfelder 2021). Section 6 will conclude.

2. Bell's theorem and the superdeterminist's response

Given that superdeterminism starts out as a response to Bell's theorem, we use this section to illustrate Bell's theorem (Bell 1964), its implications, and the superdeterminist's response. This section relies heavily on the version of Chen (2021) (which is itself a variation of Maudlin 2011 Ch. 1). We chose to follow this reconstruction of Bell's theorem because it is one of the clearest in the literature. The reader already familiar with Bell’s theorem and its implications can skip this section.

Bell’s theorem is almost universally considered as conclusively showing that nature is fundamentally non-local. To appreciate why Bell’s theorem purportedly shows this, we recap in what follows a possible way to derive Bell’s conclusion.

Let us assume that we start with a collection of calcium atoms emitting pairs of photons traveling in opposite directions. Along their paths, we can set up two polarizers at arbitrary distances, followed by two photon detectors. Each photon can either pass or be absorbed by the polarizer on its path. We say that two photons from a photon pair “agree” if they both pass the polarizer or they both get absorbed, otherwise they “disagree”.

To simplify things, imagine that the polarizers have just 3 possible directions, so angles from the vertical direction, i.e. 0, 30, and 60 degrees. It just so happens, as a matter of predictions of quantum mechanics and empirical observations, that if you run a large enough number of experiments with the polarizers at different angles, we have the following predictions.

Prediction 1. If the two polarizers point in the same direction, 100% of the photon pairs agree.

Prediction 2. If the left polarizer and the right polarizer differ by 30 degrees, 25% of the pairs disagree.

Prediction 3. If the left polarizer and the right polarizer differ by 60 degrees, 75% of the pairs disagree.

Prediction 1 is the most interesting from a philosophical perspective. It predicts that the two photons will always agree if going through two polarizers pointing in the same direction. However, two options are possible -- either they both pass the polarizer, or they both get absorbed -- and the equations of quantum mechanics are silent about which option will happen. This means that, if one measures, say, the left photon and sees that it passed the polarizer, we immediately know the result of the *right* photon, even prior to its measurement. With full certainty, the right photon will pass the polarizer too. As the two polarizers can be set at arbitrary distances, and we can make it so that the left photon hits its polarizer before the right one does, this seems to imply the famous "spooky action at a distance." If the left photon is measured to have passed the polarizer, this information seems to be instantaneously "sent" to the right photon, given that the right photon will "have" to pass its polarizer too. This occurs, and is predicted to occur, independently of the distance among the two polarizers. Prediction 1 seems then to suggest that there are non-local phenomena, viz. events that instantaneously have a causal influence on other events arbitrarily far away in space.

Some tried to resist this conclusion of non-locality. Famously, Einstein Podolsky and Rosen (1936) argued that this phenomenon must indicate that our description of quantum mechanics is incomplete. For instance, there must be properties of the photon pairs that pre-determine whether the pair will pass or be absorbed given the polarizers' direction. It is just that, so goes the argument, our current quantum mechanical formalism does not take into account these properties, hence its incompleteness. This obviously would explain the results of prediction 1 without violating the principle of locality. However, Bell's theorem put an end to this line of thought---and, according to many, once and for all. For, Bell observes, if photon pairs do have these pre-determined values that are not currently embedded in the quantum mechanical formalism and these values determine the photon behavior with respect to different positions of the polarizers, then only 8 assignments are possible (see Table 1). Other assignments are simply not possible, as they would violate prediction 1. In other words, each photon-pair starts, in this picture, with one of 8 possible fixed states "attached" to it, which will determine its future behavior. These states can be labelled with a variable λ, the so-called "hidden variable". Note that these predetermined states are assumed to determine the outcome of a photon in a *local* manner: the outcome on one side does not depend on the one on the other side. All outcomes are in Bell's picture assumed to be determined by local states carried by the photons.

	Left photon	Right photon	Percentage
(1)	P_0, P_{30}, P_{60}	P_0, P_{30}, P_{60}	$\alpha\%$
(2)	A_0, A_{30}, A_{60}	A_0, A_{30}, A_{60}	
(3)	A_0, P_{30}, P_{60}	A_0, P_{30}, P_{60}	$\beta\%$
(4)	P_0, A_{30}, A_{60}	P_0, A_{30}, A_{60}	
(5)	P_0, A_{30}, P_{60}	P_0, A_{30}, P_{60}	$\gamma\%$
(6)	A_0, P_{30}, A_{60}	A_0, P_{30}, A_{60}	
(7)	P_0, P_{30}, A_{60}	P_0, P_{30}, A_{60}	$\delta\%$
(8)	A_0, A_{30}, P_{60}	A_0, A_{30}, P_{60}	

Table 1 (from Chen 2021).

Given that the percentages are non-negative, the following must be true. (This inequality takes the role of Bell's inequality in the present model.)

(1) $\gamma + \delta + \beta + \gamma \geq \beta + \delta$

However, it can be shown that if we want to respect predictions 2 and 3, we will violate the inequality. In fact, if we set the left polarizer to 0 and the right to 30, to respect prediction 2 we have that

(2) $\beta + \gamma = 25$.

And, if we set the left one to 30 and the right one to 60, for the same reasons we have that

(3) $\gamma + \delta = 25$.

Likewise, if we set the left polarizer at 0 and the right one at 60, then we have to respect prediction 3. It follows that

(4) $\beta + \delta = 75$.

Equalities (2-4) jointly show that, as a matter of basic arithmetic, (1) is false. However, (2-4) just follow from the hypothesis that there are hidden variables and from the predictions (empirically confirmed) of quantum mechanics. Hence we have a contradiction, the inequality in (1) does and does not hold. The fact that we derive a contradiction by assuming i) a hypothesis about local hidden states or variables, and ii) the correctness of the prediction of quantum mechanics (as stressed, empirically confirmed numerous times) shows that we need to give up either i or ii. Obviously, the natural decision is to give up the former. If so, Bell's argument shows once and for all that no local hidden variables are possible and that nature is fundamentally non-local. Or so the vast majority believes.

Superdeterminism offers an alternative approach to this. In a nutshell, superdeterminism amounts to an attempt to save locality despite Bell's experiment. Here is how the superdeterministic solution works. Suppose that you are about to perform a Bell experiment with sub-collections of 100 photon pairs from a starting group of 100,000 photon pairs. The whole setting is the one described above. There is, in principle, a way to argue that the possibility of the existence of local hidden variables is not ruled out by Bell's interpretation of the experiment. Assume, to respect prediction 1, that all pairs have one of the 8 assignments of the table above. As before, let us take just three possible experimental settings. A) the left polarizer at 0 degrees and the right polarizer at 30 degrees, B) the left polarizer at 30 degrees and the right polarizer at 60 degrees, and C) the left polarizer at 0 degrees and the right polarizer at 60 degrees. We know, thanks to the predictions, that we need to expect 25% of disagreement in the A and B set-ups and a 75% disagreement in the C set-up. It is actually possible to obtain this result. Given the 8 possibilities of the table, we just need to carefully choose the photon pairs for each sub-collection. For instance, this happens if all of the following obtains:

- The collection of photon pairs that go through the A set-up (let us call this collection "*a*") is such that 25 pairs are of type 3 and 75 are of type 1.

- The collection of photon pairs that go through the B set-up (let us call this collection "*b*") is such that 25 pairs are of type 5 and 75 are of type 1.
- The collection of photon pairs that go through the C set-up (let us call this collection "*c*") is such that 25 pairs are of type 1 and 75 are of type 3.

That is, the right kind of sub-collections in the experiment get somehow correctly associated with the right set-up, so that the overall results are in accordance with the predictions of quantum mechanics. Crucially, if we further assume that $\alpha = \beta = \gamma = \delta = 25\%$ in the total photon pair collection, Bell's inequality in (1) is *not* violated. As a result, no contradiction ensues by postulating hidden variables and upholding locality. In this picture, nature is local and Bell's experiment fails to show an alleged non-locality. However, one needs to swallow the idea that, for some reason or another, when one performs a Bell experiment and sets up the polarizers, the *right* subset of photons gets chosen to go through the experiment. This should not only happen for the particular choice of polarizers as in the above example, but for any arbitrary choice of polarizers -- and choosing polarizer settings can be done in infinitely many ways. In other terms, this superdeterministic solution demands that there is a statistical dependence between the properties of quantum particles and the choices of analyzer settings. This, as noted by many, seems to imply that nature is conspiring to get the right results, and to hide its locality from us. In the next section, we shall discuss in detail this conspiracy objection and offer ways the superdeterminist can respond to this charge.

3. Superdeterminism, conspiracies, and counterfactuals of coincidence

In this section, we will first analyze what the conspiracy objection amounts to, and we will do so by resorting to a counterfactual analysis of conspiracy. Once the nature of the objection is made explicit, we will counter the objection by using an analogy from the literature on conspiracies and time travel.[1]

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[1] One might note that in two recent physics publications proposing first versions of superdeterministic theories ('t Hooft 2021, Donadi and Hossenfelder 2021) the authors explicitly claim that those theories are *not* conspiratorial.

To start, it should be noted that superdeterminism does indeed give up the principle of statistical independence, at least when it comes to the micro-level described by quantum mechanics (e.g. Lewis 2006, Myrvold et al. 2020). We acknowledge that this can be rightly seen as a shortcoming of superdeterminism. In fact, as many observed (e.g. Shimony et al. 1976, Maudlin 2019, Baas and Le Bihan 2021, Chen 2021), statistical independence is assumed in virtually all parts of the scientific enterprise. That is, whenever we have a large sample and we conduct experiments on a large enough sub-collection of the initial sample, and we find out for instance that 70% of the elements in the sub-collection have the property P, we are entitled to infer that the 70% (or a percentage sufficiently close to it) of the elements in the large sample has property P. This inference is granted by the principle of statistical independence. If the sample was randomly chosen (and it was sufficiently large), we are entitled to think that the sample is representative of the whole in virtue of the principle of statistical independence: our random choice can be assumed to be independent of the statistical properties of any collection. So, the principle of statistical independence does permeate and guide the entire scientific enterprise.

In the superdeterminist's interpretation of Bell's experiment, statistical independence is instead violated, as illustrated in the above example: the sub-collections *a*, *b*, and *c* are not representative of the full collection. For instance, the three sub-collections are not such that $\alpha = \beta = \gamma = \delta = 25\%$. So, a superdeterminist needs to give up the extremely appealing principle of statistical independence. However, by doing so, the superdeterminist retains the principle of locality. One could then argue that locality too has the ring of plausibility to it. Locality is, like statistical independence, one of those metaphysical principles that guide scientific practice. If we were to observe, for instance, that *everytime* someone claps their hand, a dog far away from the clapping *instantaneously* dies, we would not even entertain the hypothesis that the clapping and the death stand in a causal relation, despite the constant correlation. We rule out the hypothesis, or we do not even consider it, because the hypothesis implies positing a non-local type of causal relation.

One could then argue that what Bell's experiment shows us is that we either have to relinquish locality (as almost all standard interpretations of the experiment do) or statistical independence (as superdeterminism does). As both are plausible and natural principles that govern a large part of the scientific practice and theory, one could consider that both options are worth pursuing. That is, we would have a situation where Bell shows that we are forced to give up at least one plausible principle that supposedly governs our world and it is then a matter of further inquiry which route one should take. If so, this would be a point in favor of superdeterminism. Instead of being quickly dismissed, it would become an option worth exploring.

But many authors believe that the charges against superdeterminism are so heavy that the balance hopelessly tips in favor of non-locality and against superdeterminism. Let us consider again the superdeterministic picture in the context of the Bell experiment as sketched in the preceding section. To run the experiment, one needs to choose the set-ups of the two polarizers: this can be done for instance with a random number generator or by the free choice of an experimenter. At the same time, according to superdeterminism, nature would have to select for each set of analyzer choices, by whatever method they are fixed, the "right" sub-collection of photon pairs. In the example of the previous section, if the experimenter sets the left polarizer at 0 degrees and the right one at 30 degrees (set-up A), then the sub-collection of photon pairs that goes through this set-up has to be the sub-collection a; and likewise for B and b and for C and c. This seems hard to digest, if one assumes that the selection of these sub-collections and the procedure of setting up the polarizers are statistically independent.

In order to go further in this analysis, we believe it is instrumental to recast the argument in terms of counterfactuals. At first sight, the superdeterministic picture seems to require the truth of suspicious counterfactuals. Suppose that as a matter of fact A and a are selected. It then seems that the following must be the case:

(C) If the set-up B had been chosen, then the sub-collection *b* would have been selected.

In fact, the set-up B paired with collections *a* or *c* is not a possibility within superdeterminism.[2] However, (C), under a standard understanding of the semantics of counterfactuals, seems to be just *hard to believe*. According to the standard Lewis-Stalnaker treatment of counterfactuals (Lewis 1973 and Stalnaker 1968), a counterfactual "if it had been the case that P then it would have been the case that Q" is true at a world *w* iff the consequent is true in the possible world most similar to *w* in which the antecedent is true.[3] If in the actual world A and *a* had been selected, it's unclear why a possible world where B and *b* are selected is closer to the actual world than a world where B and *a* are chosen. On the contrary, the latter B-world, the one where the consequent is false, seems to be more similar to the actual world---for it seems natural to assume that the choice of the polarizer angles and the choice of the sub-collection are two independent events. This in turn naturally inclines us to keep fixed the actual choice of *a* when evaluating the counterfactual (C). This would then make the counterfactual (C) just false, thereby seemingly undermining the superdeterministic strategy. To suppose that the B-*b* world is more similar to the actual one than the B-*a* world is to suppose that, an opponent of superdeterminism would say, nature conspires behind the scenes. That is, an incredibly numerous series of coincidences would take place. If we run the Bell experiment multiple times, so the argument goes, we will always encounter a series of surprising and unexpected coincidences. The set-up A will always be matched with the sub-collection *a*, the set-up B with the sub-collection *b*, and the set-up C with the sub-collection *c*. No matter how many times we run the experiment, these coincidences will always take place.

So, based on these considerations, one might argue that the strategy of rejecting locality and the strategy of rejecting statistical independence are not, after all, theoretically on a par. For, so goes the anti-superdeterminism argument, the

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[2] To be more precise, the consequent in (C) should be "*b* or a sub-collection of the same statistical profile as *b* would have been selected". This is so because other sub-collections could be in accordance with actual observations and superdeterminism. For instance, in the case of set-up B, the following would do: The collection of photon pairs that through the B set-up (let us call this collection "*b**") is such that 25 pairs are of type 5 and 75 are of type 3. In the remainder of the paper we will ignore such complication, as the gist of our argument should remain clear without this specification.

[3] Lewis's and Stalnaker's accounts differ in details, and the definition used here is imprecise. However, it captures the spirit of their proposal and it is precise enough for our purposes here.

strategy of rejecting statistical independence while upholding locality forces us to accept the truth of suspicious counterfactuals of coincidence such as (C).

To sum up the argument so far, the superdeterministic strategy of saving locality comes with a seemingly suspicious implication about nature conspiring behind the scenes by making coincidences happen on a regular basis. *We argue that the charge of conspiracy against superdeterminism lies precisely in counterfactuals such as (C).* That is, people who find superdeterminism a conspiracy theory and hence a non-starter do it because they think that superdeterminism implies (C) and (C) is just hard to believe. Certainly it seems more than natural to take such a counterfactual to be false.

However, we think this whole argument is not conclusive. In the remainder of the section, we will challenge it by drawing upon insights from another area of inquiry, viz. the philosophical literature on the possibility of time travel. We will argue that the relevant counterfactual in this debate should not be (C), but rather another one that we will present shortly. To make our point, we will look at Ted Sider's work (2002) on *Time Travel, Coincidences, and Counterfactuals*, and submit that some of the arguments used there can be employed in the debate about superdeterminism. To be explicit, we do not need here to assume that time travel is a physical possibility. We just want to submit that the current debate on coincidences in the time travel literature may shed new light on the issue of coincidental conspiracy in the present context.

As it is well known in the time travel literature, time travel cannot result in changes in the past (see, among others, Lewis 1976 and Arntzenius and Maudlin 2002). Suppose a time traveler travels back in time and tries to kill his younger self. We know the time traveler will not succeed, or else contradictions will ensue. For if the time traveler kills his younger self (and we bar resurrection), he will not grow up to later jump back in time and kill his younger self. Even if time travel were possible, autoinfanticide by exploiting time travel is not.[4] Time travelers who attempt to kill their younger selves will fail. Why do they fail? The standard answer

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[4] There is actually nothing special about autoinfanticide. Time travelers can never change the past. They, for instance, cannot kill Baby Hitler, as Hitler did not die when he was a baby. This does not mean time travelers cannot affect the past (see Lewis 1976 for a distinction between changing and affecting the past)

in the literature is that they would fail for ordinary reasons: a sudden change of heart, the bullet will surprisingly miss the target, a bird would just pass through and stop the bullet, failure of nerves, or (famously) the time traveler would slip on a banana peel. In an interesting twist, Horwich (1987, ch. 7) discusses a thought experiment devised to cast some doubts on this idea. What would happen, so goes the thought experiment, if a future Time Travel Institute for Autoinfanticide were to send back in time thousands of time travelers attempting to kill their younger selves. Despite (we can imagine) their training, their loaded weapons, their strong motivations, and the easy unprotected targets, they would *all* fail---for autoinfanticide is impossible. A big series of coincidences must be *guaranteed* to happen to stop their attempts. We would have to believe in the following counterfactuals of coincidence:

(T1) If time traveler 1 were to attempt to kill his younger self, he would slip on a banana peel, or his nerves would fail, or...
(T2) If time traveler 2 were to attempt to kill his younger self, he would slip on a banana peel, or his nerves would fail, or...
(T3) If time traveler 3 were to attempt to kill his younger self, he would slip on a banana peel, or his nerves would fail, or…

In *all* attempts, coincidences are guaranteed to happen and the relative counterfactuals need to be true. However, one might use this thought experiment to run an argument against the possibility of time travel.[5] After all, big series of coincidences do not happen, so we should not expect them to happen – the same argument we encountered above against superdeterminism. But that's what the metaphysical possibility of time travel seems to imply.

Moreover, the counterfactuals T1-3 just seem false, for in the thought experiment we imagine that the time travelers have what it takes to kill and that conditions are ideal. The only thing that stops them must then be a big series of coincidences. But, as said, we do not expect big series of coincidences to happen. Sider, however, argues that there is nothing wrong in considering those

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[5] It should be noted this was not Horwich's intent.

counterfactuals as true. To show that, he discusses the following two counterfactuals.

> (W) If Tim were to throw the stone at the window, Tim would slip on a banana peel or hit a passing bird or…
> (W*) If Tim were to throw the stone at the window but the window did not subsequently break, then Tim would slip on a banana peel or hit a passing bird or....

Suppose Tim's throwing abilities are just normal so that in ordinary circumstances he would break a window with a stone. If so, (W) just seems wrong. That is, we have no reason to think that some strange coincidence *would* happen and stop the breaking. At most, we can say that they *might* happen. However, (W*) seems to be of a different nature. As Sider observes, in (W*) there is some difficulty built in the antecedent. The antecedent is "hard" to make true, as it counterfactually considers circumstances where Tim throws a stone, Tim has the ability to break the window, conditions are ideal and he attempts to do so. Yet, he fails. In these counterfactual circumstances, where the failure is built in the antecedent, it's normal to expect some coincidental event. In other words, whereas (W) seems false, (W*) strikes us as true. Crucially, Sider continues, the counterfactuals (T1-3) are just like (W*). In (T1-3), it is again the case that the difficulty is built into the antecedent. In fact, we consider individuals (our time travelers) who are perfectly suited and equipped to kill the victim and yet they fail. Those circumstances are "hard" to make true, and thus it is no wonder that they require a continued series of coincidences to be true. Moreover, we considered (W*) as being true. If (T1-3) are just like (W*), then (T1-3) are true as well, despite initial appearances to the contrary. In other words, there is nothing surprising nor strange with coincidences "guaranteed to happen" in the case of time travelers attempting to kill their younger selves.

Why does this have a bearing on the superdeterministic strategy? Let us briefly recap the superdeterministic strategy. Superdeterminists want to offer a theory that: (i) is in accordance with the predictions of quantum mechanics, and (ii) saves locality. To do so, the superdeterminist posits the existence of hidden variables. As the prediction 1 of quantum mechanics (see previous section) needs to be respected, the hidden variables of the photon pairs can take only one of those 8 possible values. Given the nature of the other 2 predictions, the superdeterminist needs to posit the "coincidental" match between the set-up and the sub-set of photons that go through the set-up in a Bell experiment. Returning to the example given above, this seems to imply that the superdeterminist has to believe that when, say, set-up A and sub-collection *a*are selected*,* counterfactuals of coincidence such as (C) are to be true.

(C) If the set-up B had been chosen, then the sub-collection *b* would have been selected.

As said, (C) just seems hard to believe because in the consequent we have a "coincidental event", namely a sub-collection that differs in nature from the general collection. Yet the parallel with time travel and the counterfactuals of coincidence now comes to play. Notice that within the superdeterministic picture we are assuming locality. That is, the superdeterminist takes the actual world to be a world where locality holds. The relevant counterfactual to consider is not (C) then, but rather

(C*) If the set-up B had been chosen and nature is local, then the sub-collection *b* would have been selected.

With (C*), we have again a case where the consequent features a "coincidental event", i.e. the anomalous sub-collection *b*. Whereas we think that coincidences *might* happen, we do not normally think that they *would* happen. However, here a difficulty is built into the antecedent of the counterfactual. The antecedent asks us to consider counterfactual scenarios where B is selected and nature is local, while we have to keep fixed the predictions 1-3 of quantum mechanics. Those described circumstances *require* unlikely coincidences to be true. That is, the conditions built in the antecedent are hard to make true. One of the few ways to make them true is that the sub-collection *b* is selected. If so, there is nothing surprising, remarkable, nor suspicious with considering (C*) as true. (C*) just is true. Counterfactuals of coincidence are sometimes true, and (C*) is one of those cases.

Notice also that (C*) bears similarities with (W*) and (T1-3). In (W*), the conditions described in the antecedent are difficult to make true: We are asked to consider a situation where Tim fails to break a window despite the fact that he has the ability to do so and conditions are ideal. In (T1-3) something similar goes on. The antecedent requires to consider a situation where people are perfectly equipped to kill, find themselves in favorable conditions and with the intention to kill, yet they try and fail. Similarly for (C*). Here the antecedent requires us to consider a situation where locality holds and the predictions of quantum mechanics are fixed. We are also asked to make it the case that in the counterfactual scenario the set-up B is chosen. To make all the above facts hold together, only a few circumstances would work. One of the few is that the sub-collection *b* is selected. But, we noted that it is very natural to consider (W*) and (T1-3) as true. If (C*) is indeed similar to them, as we argued, then it seems natural to say that (C*) is true.

One could reply that by focusing on (C*) rather than (C) we are just assuming what a superdeterminist wants to show, i.e. that nature is local. But this seems to be a too hasty conclusion. Remember the initial dialectic. Bell's experiment shows us that we need to give up at least one of the two principles: locality or statistical independence. Both are well-established principles that are largely assumed in all parts of scientific practice. One could then think that the options of dropping either of them are on a par. But, opponents of superdeterminism argue that the option of dropping statistical independence to save locality comes at a great cost, i.e. the cost of believing that nature *conspires* to guarantee that strange coincidences always happen, and hence the two options are not on a par. However, if we are correct, things do not stand in that way. Once the worry about the "coincidental" nature of superdeterminism is spelled out, i.e., once we realize that the relevant counterfactuals within superdeterminism are those such as (C*) and that there is nothing remarkable or surprising about (C*) being true, then there should be no resistance in accepting (C*)-type counterfactuals as true. The coincidental appearance is just what is required by the fact that it is difficult to make the antecedent true. If so, the option of rejecting statistical independence (superdeterminism) and the option of rejecting locality (other interpretations of quantum mechanics) are again on a par and further inquiry is needed to settle the issue.

In conclusion of this section, we believe superdeterminism cannot be so quickly dismissed based on the argument that it implies strange and hard to believe coincidental events. The charge against superdeterminism amounts to rejecting counterfactuals of coincidence as (C). But we showed here that counterfactuals of a similar type are believed to be acceptable by many philosophers. Lastly, note that the superdeterminist could arguably rely on an argument from physics to tip the balance in her favor: many physicists believe that non-locality implies a violation of Lorentz invariance and relativity theory. This point was raised, to start with, by Bell himself (see the conclusion of his 1964). The superdeterminist may emphasize that her favorite view may look counterintuitive, but does notviolate any established law of physics proper.

4. Superdeterminism and laws of nature

In this section we address a recent objection by Baas and Le Bihan (2021).[6] Baas and Le Bihan argue that superdeterminism raises a worry related to the laws of nature. As it is well known, the philosophical literature provides different accounts of the laws of nature. As they observe, we can count at least four accounts: 1) *Primitivism* (cf., among others, Maudlin 2007) 2) *Humeanism* (cf., among others, Lewis 1994) 3) the *Dispositionalist view* (cf., among others, Bird 2005 and Vetter 2012), and 4) the *Universalist view* (cf., among others, Armstrong 1978, 1983). According to Baas and Le Bihan, superdeterminism is compatible only with

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[6] Baas and Le Bihan raise other worries, but those we treat in this and the next section are considered the most pressing ones by these authors. Another worry is the a-typicality and/or fine-tuned nature of the cosmological initial conditions that superdeterministic theories would need (this problem is closely related to the conspiracy objection and the problem treated in the present section). In any case, we agree with Baas and Le Bihan that fine-tuning is not specific to superdeterminism and seems not an ultimate objection. We believe the same holds for a-typicality. Any deterministic physical theory that makes a prediction "at token level", i.e. about detailed facts of the world, needs to use unique initial values (in such deterministic "initial value problems" unique initial values are mapped on unique solutions). Finally, in (Donadi and Hossenfelder 2021) counterarguments against the charge of a-typicality / fine-tuning are given by explicit construction of a superdeterministic toy model that is, according to the authors, neither fine-tuned nor conspiratorial.

Humeanism. This is taken to be a disadvantage, since supporters of other views on the laws of nature would find superdeterminism unattractive. Their argument relies on the assumption that superdeterminism needs to posit an ontological dependence between the laws of nature and the initial conditions of the universe.

The assumption about ontological dependence relies on the fact that, according to many, superdeterminism needs to posit a sort of coincidental match between the initial conditions of the universe and the dynamical laws described by the Schrödinger equation of quantum mechanics. The idea is that some event (or some collection of events) in the causal past of the universe, a past that ultimately goes back to the very initial conditions of the universe, causes *both* the choice of the polarizers in a Bell-like experiment and the selection of the sub-collection that goes through the experiment. This would in turn ensure that the "right" sub-collections always get assigned to the "right" set-ups.

This, in Baas and Le Bihan's view, implies a dependence between the laws of nature (the Schrödinger equation) and the initial state of the universe. In fact, had the initial conditions been different, so the thought goes, the laws of nature would also have been different. They then go on observing that this is a counterfactual that only a supporter of Humeanism about the laws of nature could accept. For, under Humeanism, laws are not ontologically independent entities. On the contrary, under Humeanism laws just supervene on the mosaic of facts (Lewis 1994). It is thus not problematic for a Humean to argue that different events at a specific time, including the first time, yield a different set of laws. But, this ontological dependence between initial conditions and laws is problematic for the other three accounts of laws, as in those accounts laws enjoy a degree of independence from what events there are, i.e. the same set of laws is compatible with different events and in particular with different initial conditions.

We agree that if superdeterminism were compatible only with Humeanism, this would be a problem for superdeterminism. However, we do not think that this is the case. It should be noted that a superdeterminist considers the current equations of quantum mechanics as incomplete. That is, according to a superdeterminist, there must be deeper laws of nature that take into account what we now temporarily call "hidden variables" and dictate their dynamical behavior over time. Therefore, it seems too hasty to claim that under superdeterminism there is a (suspicious) ontological dependence between initial conditions and laws of nature: we do not know yet how such a theory would look like.

Proponents of superdeterminism believe it is possible to construct theories with new variables, while these new variables are very likely *not* all the variables of all particles at the Big Bang (this would seem amount to an intractable phase space) – *even if these variable are assumed to exist and to be superdeterministic*. Similar moves are not rare in physics: for instance, statistical mechanics assumes that detailed mechanical properties of all particles *exist* even if they cannot be *known* in all detail; and it integrates-out these variables by statistical techniques, leading to new tractable variables such as the partition function. Indeed, this is what happens in arguably the most solid first approach towards a full-fledged superdeterministic theory, 't Hooft's Cellular Automaton Interpretation of quantum mechanics ('t Hooft 2014, 2016, 2021). In 't Hooft's theory the superdeterministic variables are integrated-out[7], and an effective hidden-variable theory is constructed with effective hidden-variables *that play their usual role*. There is no ground to assume an ontological dependence between the initial values of these variables and the effective laws. In (Donadi and Hossenfelder 2021) this strategy of building a "higher level" theory by integrating-out hidden variables is also used[8]. As said, such a construction of effective theories is very similar to what happens in statistical thermodynamics, where the mechanical variables of the ultimate constituents of matter are integrated-out and give rise to new, effective variables. In such an effective theory the link between the new variables (and their initial values) and the laws of statistical thermodynamics is the usual one, even if a gigantic phase-space of unknowable "deeper" variables is assumed to exist.

Hence, to the least, we can acknowledge that some (reputable) physicists do believe that the construction of realistic superdeterministic theories is a worthy research project, compatible with the usual practices of physics; and in the published works there is no trace of an ontological dependence of the laws (of these theories) on the initial conditions. In sum, the argument by Baas and Le Bihan surely has some traction; but it seems that already published attempts at providing a superdeterministic theory have ways to respond to their objection.

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[7] See ('t Hooft 2021), Eq. (14) and accompanying text.

[8] Cf. e.g. (Donadi and Hossenfelder 2021) p. 8.

5. The objection from the impossibility of science.

The third argument against superdeterminism that is voiced by authors as Shimony et al. (1976), Maudlin (2019), Baas and Le Bihan (2021), and Chen (2021), boils down to the idea that the enterprise of doing science would not be possible in a superdeterministic world. Maudlin (cited by Chen 2021) phrases it this way (2019):

> "If we fail to make this sort of statistical independence assumption, empirical science can no longer be done at all. For example, the observed strong robust correlation between mice being exposed to cigarette smoke and developing cancer in controlled experiments means nothing if the mice who are already predisposed to get cancer somehow always end up in the experimental rather than control group. But we would regard that hypothesis as crazy."

Again, the idea is that experimental science is only possible if our choices of testing conditions are independent of the physical properties that determine experimental outcomes – an assumption violated by superdeterminism. To be definite, Chen (2021), for example, defines stochastic independence in this way: "we assume that the direction of the polarizer can be set independently of the collection of incoming photon pairs".

Now, while we agree that superdeterminism implies *some form of* statistical dependence, we believe that there are arguments for the idea that this dependence may well be innocuous, after all. To make our point, it is necessary to define "statistical independence" in a slightly more precise way. Clearly, the statistical independence that is used in the mathematical proofs of the Bell inequality, is a well-defined concept in probability theory, and holds between statistical variables. By definition, variables x and y are *in*dependent (or "de-correlated") *iff* $P(x|y) = P(x)$ (for all values of x and y) where both x and y may actually represent a series (n-tuple) of variables; if the "$\neq$" sign holds (for some values), then x and y are said to be dependent. This definition is based on the concept of conditional probability (($P(x|y)$). Since conditional probabilities are defined via joint probabilities, it is easy to show that a mathematically equivalent definition of independence is: $P(x, y) = P(x)P(y)$. In the context of Bell's theorem, the variables between which the supposedly essential independence should hold are, on the one hand, the left and right analyzer variables, call them θ_1 and θ_2 respectively, and, on the other hand, the local hidden variables λ. In a formula, independence boils down to:

$$P(\lambda|\theta_1, \theta_2) = P(\lambda). \qquad \text{(Eq. 1)}$$

Superdeterminism violates equation (1) since it assumes that the particle properties λ (or slightly more generally, the properties or states that determine the experimental outcomes, cf. the toy model of section 2) are somehow statistically dependent on the (choice of) the analyzer angles. Eq. 1 is indeed the mathematical expression that is used in proofs of the Bell inequality (see e.g. Hossenfelder and Palmer 2020 Eq. 3). So any superdeterministic theory assumes, by definition, statistical dependence, i.e.:

$$P(\lambda|\theta_1, \theta_2) \neq P(\lambda). \qquad \text{(Eq. 2)}$$

First, it is clear that statistical independence is ubiquitous in nature, and an experimentally well-confirmed assumption in countless experimental situations. For instance, if θ_1 is chosen by Alice, and θ_2 by Bob, and if both experimenters have no pre-established plan, then their random choices of the values of these angles will clearly be independent. Similarly, random number generators would lead to independent angles. This independence can easily be experimentally verified: it suffices to determine the probabilities $P(\theta_1, \theta_2)$, $P(\theta_1)$and $P(\theta_2)$ (as relative frequencies in an experiment in which both Alice and Bob choose say 1000 angles), and then to compute that $P(\theta_1, \theta_2) = P(\theta_1)P(\theta_2)$ (or, equivalently, $P(\theta_1|\theta_2) = P(\theta_1)$). This independence seems so obvious that no-one would even bother to do the experiment! Similarly, there is independence say between the fluctuations of the terrestrial magnetic field in a given spot in Paris, and the half-life of a radioactive atom in a lab in New York. There is a ubiquitous independence between the "usual" variables we encounter; and this is indeed a prerequisite to do science. On the other hand, in certain interesting cases there *is* statistical dependence. For instance, in a Bell experiment there is dependence between the left and right electron spins or photon polarizations, as illustrated in section 2. As a numerical example, in the case of photons in a "singlet" state the mathematical expression for the joint probability of the left and right polarization (x and y) is given by:

$$P(x, y|\theta_1, \theta_2) = \frac{1}{4}[1 + xy\cos(\theta_1 - \theta_2)]. \qquad \text{(Eq. 3)}$$

This expression covers the examples given in section 2 and accounts for instance for the fact that if $\theta_1 = \theta_2$ the polarizations are perfectly correlated[9]. Note that the probability in Eq. 3 cannot be factorized in a product of the type $P(x)P(y)$. There is also correlation between (x, y) and (θ_1, θ_2): $P(x, y|\theta_1, \theta_2) \neq P(x, y)$.

Now, we submit that the argument that the superdeterminist could invoke to justify Eq. 2, exploits two ingredients. The first is that the dependence relation she contemplates involves a *highly specific class of variables* λ, not just the "usual" physical properties. As we will detail a bit further, on the usual reading these variables are part of a theory that describes the Big Bang (and everything after it), so a (still elusive) theory of quantum gravity, or rather a (still more elusive) "Theory of Everything" (ToE). The second ingredient of the argument is that empirical verification of independence as in Eq. 1 is subject to empirical uncertainty. Normally, experimentally determined variables X come with an unavoidable measurement error, so are characterized by a certain empirical precision limit or "uncertainty" ΔX (this is usually formalized as: $X = X_0 \pm \Delta X$, where X_0 is the experimentally most likely value of X). Likewise, an experimental "probability" P, determined via a ratio of counts, comes with an uncertainty ΔP. This uncertainty varies as 1/N, where N is the number of trials (precise probability measurements need a large number of trials).

Now, the first part of the argument is rather straightforward and well-known. Typically, superdeterminists justify Eq. (2) by pointing to the logical and physical possibility that the "free" choice of analyzer angles is itself a physical process (materialized by a highly complex neural, but ultimately still physical, process in the experimenter's brain), and that this process and all the physical properties involved are themselves causally determined by preceding events. This

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[9] Indeed, from Eq. (3) follows that $P(x = +1, y = +1|\theta_1, \theta_1) = P(+,+) = ½ = P(-,-)$; and $P(+,-) = P(-,+) = 0$, corresponding to perfect correlation.

causal chain between successive events and processes is assumed to reach from the neural choice event to the Big Bang. Since events and processes are in this picture all described by physical properties, i.e. variables, the conclusion is that all variables occurring in theories and experiments, also θ_1 and θ_2, are determined by, and therefore statistically dependent on, the λ-variables that constitute the ToE describing the Big Bang. Ergo, Eq. (2) is the correct equation after all, or so argues the superdeterminist, *if the λ are interpreted as the variables of the "ab initio" or "ultimate" ToE* describing all details of the universe starting from time = 0.

Importantly, this argument has more traction, we believe, if one realizes that the λ are truly unique, in the most absolute sense: they are the variables occurring in the ultimate ToE – not the mundane variables we encounter every day, for which statistical independence remains obvious. Note that the above argument still holds *even* if physicists would never be able to construct such a ToE in practice. One may assume that it exists, as is usual practice in physics; several physicists are working on laying the basis for at least effective theories ('t Hooft 2014, 2016, 2021, other examples in Hossenfelder and Palmer 2020, Donadi and Hossenfelder 2021).

But this argument has a sting to it; it is here we need the second ingredient. Indeed, if the just sketched picture is correct, then the most natural assumption is, it seems, that somehow *all* events (variables) should remain correlated *via their common causes*, the λ taken at the Big Bang. But as noted above, statistical independence is ubiquitous, for instance between the freely chosen angles in a usual Bell experiment: $P(\theta_1, \theta_2)= P(\theta_1)P(\theta_2)$, as one can verify. But in the superdeterministic picture θ_1 and θ_2 should be correlated, since they have common causes. Still, we believe there is a way around this problem, using our second ingredient: it seems natural to assume that even if this correlation exists *as a matter of principle*, it is not measurable *in practice* – recall that every measured probability has a measurement error. In order to measure the highly refined correlation between θ_1 and θ_2, or the correlation in (Eq. 2), one would need to have control over the λ, and that seems impossible. In order to detect correlation between variables, one usually needs tightly controlled experiments, fixing a whole series of experimental variables[10]. For instance, in order to measure the correlations between the photons in a Bell experiment, one needs extremely draconic control over a wide range of physical variables constituting the experiment and its environment; quantum experiments are fragile and de-coherence ubiquitous. Thus, correlation can only be shown to exist in highly sophisticated experiments, at least when we probe quantum variables, let alone the sub-quantum variables λ. In a simple picture: the correlations between λ and the analyzer angles originate in a past that is so distant that they become undetectably weak. So the correlations of (Eq. 2) involving the variables of the final ToE *exist*, but are practically inaccessible.

Note that there is a marked difference with the correlations of Eq. (3) that exist among the quantum variables (x, y) and the macroscopic angles (θ_1, θ_2). The values of these four variables are 'actualized' in the Bell experiment: the numerical values that occur in Eq. (3) are the values of (x, y) and (θ_1, θ_2) *taken at the time of measurement*. In Eq. (2), the values of λ are 'old': they are taken at the Big-Bang. That could explain why we do see Eq. (3) in experiments, while Eq. (2) is practically inaccessible even if theoretically correct. One could object here that the macroscopic correlations between θ_1 and θ_2 should then also be visible, since both angles can be actualized in experiments. But these variables θ_1 and θ_2 are surely not part of a fundamental physical theory (such as quantum gravity or even quantum mechanics). So a complete argument why we often do not see correlations between macroscopic variables while we can see them in quantum experiments, must also assume that fundamental degrees of freedom have a stronger tendency to remain detectably correlated[11] – if they are accessible in experiments. In sum, it is conceivable that correlation between variables is usually only visible if at least one of the correlated variables belongs to a fundamental

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[10] This is especially the case when the two correlated events are in an indirect, distant causal relation, e.g. when they are widely separated in time and/or space and when they are causally connected via many intermediate events/causes. This would clearly apply to the correlations in (Eq. 2).

[11] "since their birth at the Big Bang, or closely afterwards", one might add, somewhat metaphorically. Note that the idea of universal correlation is very natural in quantum field theories, supposedly already valid shortly after the Big Bang.

theory (e.g. a quantum variable as in Eq. (3)) *and* if all variables can be actualized in experiments[12].

This concludes our two-tiered argument against the claim that superdeterminism is at odds with the experimental statistical independence we need to do science. Superdeterminism boils down to a *theoretical*, *in-principle* dependence (on the ab-initio variables of the ultimate ToE), a dependence which may well be experimentally undetectable for all practical purposes. Indeed, it is not just any dependence, but a very unique dependence on the ab-initio variables of the ultimate ToE. In order to understand what happens in a Bell experiment "under the surface", one would have to take these correlations of (Eq. 2) into account (by means of a hypothetical ToE), even if they are unmeasurable, just as the correlations between many other (e.g. macroscopic) variables are undetectable for all practical purposes. Chen (2021) comes to the conclusion that "it is logically consistent for one to claim that statistical independence is false about microscopic systems but for all practical purposes true of macroscopic systems". We have given here a possible answer to his question what reasons we have for thinking that this is true in a superdeterministic theory. By the same token, we have taken up the challenge proposed by Baas and Le Bihan in the conclusion of their (2021) to "provide an explanation [of why statistical independence is often valid in the macro-world but not for quantum systems] in order to connect superdeterminism to the rest of science".

6. Conclusion.

We have argued here that superdeterminism may not be as counterintuitive as often believed. We provided counterarguments to worries that were recently elaborated in detail by Chen (2021) and Baas and Le Bihan (2021), relating to the conspiratorial and coincidental nature of superdeterminism (section 3), its exclusive compatibility with a restricted Humean account of laws (section 4), and its tension with the usual methodology of science (section 5). In the wider

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[12] The exception being macroscopic events *that have a recent or strong causal link*, say between throwing a rock and the window breaking, or between the positions of earth and moon.

literature, the most frequently encountered charges against superdeterminism concern its conspiratorial nature and its relinquishing of the statistical independence needed for doing science. As to the latter worry, we argued that statistical dependence may exist in theory (in an elusive ToE), but is undetectable in many (macroscopic) instances. As to the former worry, one important goal of this article was to press philosophers to have a closer look at the notion of "conspiracy", a concept that seems heavily subjectively tainted. We opened this debate by referring to literature from time travel, and argued that in this body of work similar counterfactuals as those implied by superdeterminism are considered acceptable. Finally, we briefly noted that our arguments align with the conclusions of recent models proposed by physicists ('t Hooft 2021, Donadi and Hossenfelder 2021). The conspiratorial-looking correlations needed for reproducing the quantum results in a Bell experiment may exist at a deep, fundamental level, but may not be observable, and the variables describing these all-pervading correlations may not be necessary for building effective superdeterministic theories.

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