Time's Direction and Orthodox Quantum Mechanics: Time Symmetry and Measurement

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Abstract

It has been argued in various places that measurement-induced collapses in Orthodox Quantum Mechanics yields a genuine structural (or intrinsic) quantum arrow of time. In this paper, I will critically assess this proposal. I begin by distinguishing between a structural and a non-structural arrow of time. After presenting the proposal of a collapse-based arrow of time in some detail and discussing some criticisms it has faced, I argue, first, that any quantum arrow of time in Orthodox Quantum Mechanics cannot be defined for the entire universe and, second, that it requires non-dynamical information to be established. Consequently, I deliver that any quantum arrow of time in Orthodox Quantum Mechanics is, at best, local and non-structural, deflating the original proposal.

Keywords: Arrow of time – Quantum Mechanics – Collapse – Measurement

1. Introduction

Whether non-relativistic quantum mechanics (QM henceforth) exhibits an arrow of time has been to a great extent an interpretation-dependent matter. The problem has largely depended upon which the dynamics of QM is and whether it is time-reversal symmetric or not. On the one hand, it has been widely accepted that, as long as quantum systems evolve unitarily according to a free Schrödinger-type equation, QM is time-reversal symmetric, and thereby, it exhibits no arrow of time, at least *structurally*. On the other, it has been argued that some interpretations of QM introduce some time-reversal asymmetric elements in the dynamics that render QM time-reversal asymmetric, which reflects a structural preference for one of time's directions. Whereas *bare* QM, Wave-Function Realism, Everett's relative-state and Many-World interpretation would fall into the former side, the so-called collapse theories would definitively fall into the latter. So, defenders of an in-built arrow of time in QM have seen in collapse theories of either version a fertile terrain for upholding a quantum arrow of time.

From a very broad viewpoint, collapse theories basically consist in introducing a non-linear and stochastic dynamics in the quantum formalism, so that the quantum systems evolves generally according to some Schrödinger-type equation, but under some circumstances, they undergo a "hit" or "jump" that collapses their quantum states (or that "reduces" their wavefunctions) onto an eigenstate of some observable. The introduction of these "jumps" intends to account for the classical behavior of macroscopic systems by modifying the unitary dynamics of QM. Though the idea of "reduction" and "stochasticity" pervade any collapse-type theory, specific versions diverge over *how* collapses are brought about, and *under which circumstances* they are brought about. The first proponents of a collapse-type theory held that collapses were brought about any time a measurement is performed. These measurement-induced collapses (MIC) basically compose the so-called "Collapse Postulate", or "Projection Postulate" (PP henceforth). This view became a sort of orthodoxy in the physicists' community up to our days and is one of the dynamical principles (or axiom) of the Orthodox Quantum Mechanics (OQM) along with the Schrödinger equation. Yet, in the 70s, a new family of collapse theories was born –the Dynamical Reduction Program (DRP). Aiming at overcoming many of MIC's issues, while retaining some of its essential features, its defenders developed a collapse theory on the basis of a *single* dynamics, where those "jumps" were brought about spontaneously, independently of any measurement procedure. Both MIC and DRP introduces a dynamical mechanism that would not only guarantee that measurements will always have outcome, but also would break the time-reversal symmetry of the theory –quantum systems collapse, but they do not *un*collapse.

This paper will focus on OQM and, particularly, on MIC. Several physicists and philosophers have suggested that MIC lays the groundwork for a *quantum* arrow of time –since MIC is an axiom of OQM, and MIC turns out time-reversal asymmetric, OQM exhibits an in-built arrow of time Setting aside the numerous interpretative issues OQM has had to face, the idea is persuasive and has received considerable support in the physicists' community as well as in the philosophers'. However, it has not been fully clear what is the scope, and what are the details of such a claim.

Some philosophers have distinguished between a fundamental (or structural) and a non-fundamental (or emergent) arrows of time. Others have drawn the distinction between local and global, or between objective and non-objective arrows of time. Under the assumption that OQM is a tenable interpretation of QM, what sort of quantum arrow of time MIC yields? How does it come to establish a genuine time-reversal asymmetry, if it is really so?

In this paper, I will assess MIC in relation to its time-asymmetric nature and the resultant arrow of time. In the first place, I will analyze and discuss opposing positions with respect to whether MIC yields a genuine time-reversal asymmetry and, consequently, a quantum arrow of time. Then, I will argue that the sort of time-reversal asymmetry that MIC provides us just yields a *local*, *non-structural* arrow of time, which largely relies on non-dynamical information about the quantum state. The structure of the paper is as follows. In Section 1, the theoretical basis of MIC and OQM will be briefly presented. In Section 2, the distinction between a fundamental and a non-fundamental arrow of time will be introduced along with the relationships between MIC and a quantum arrow of time according to its main defenders. In Section 3, some criticisms against a quantum arrow of time induced by MIC will be discussed. In Section 4, my main arguments will be laid out. I will first show why MIC's arrow of time is, at best, non-structural. Then, I will show why it is categorically local. Finally, some concluding remarks and guidelines for future work.

2. Quantum Evolution and Measurements: OQM

The origin of OQM, and of MIC in particular in the 30s, is some primitive form of the so-called *measurement problem.* The literature on this is abundant, so I will not get into details here (see Albert 1992, Maudlin 1995, Wallace 2007). In a nutshell, the *measurement problem* can be posed in the following plain way: QM involves an intrinsic paradox that seems to be unsurmountable from QM's means alone, namely, that what QM's dynamics (i.e. a Schrödinger-type dynamics) predicts is flagrantly in contradiction with what we observe in experiments. So, it seems that the theory is in need of further revisions to escape the paradox. Otherwise, QM's dynamics yields *wrong* predictions. OQM was one of the first attempts to overcome this setback in the development of the new quantum theory –the *bare* QM was in need of an additional postulate, MIC, that accounted for what was macroscopically observed in experiments.

In essence, MIC prescribes that quantum systems undergo a radically different evolution when measured. Hence, OQM prescribes a two-fold dynamic for quantum systems: either they evolve unitarily according to some Schrödinger-type equation when no measured, or they experience a "jump" or "collapse" caused by a measurement process. In 1930, Paul Dirac presented MIC to bridge the gap between QM's dynamics and experiments:

> "When we measure a real dynamical variable ξ, the disturbance involved in the act of measurement causes a jump in the state of the dynamical system (…). In this way we see that a measurement always causes the system to jump into an eigenstate of the dynamical variable that is being measured, the eigenvalue this eigenstate belongs to being equal to the result of the measurement". (Dirac 1935: 36)

Few years after, John von Neumann (1955[1932]) proposed a model for (ideal) measurements that has become canonical in the field, giving a more refined version of MIC. Von Neumann's main statement of MIC comes in the following way:

> "we have therefore *two fundamentally different types of interventions* which can occur in a system S (…) first, the arbitrary changes by measurements (…). Second, the automatic changes which occur with the passage of time". (von Neumann 1955: 351. Emphasis added)

Both sorts of interventions (or processes as he has also called them) are of a fundamentally different nature: while the first is statistical, the second is causal. In analyzing in detail these two types of processes, von Neumann claims:

> "Why then do we need the special process 1 for the measurement? The reason is this: In the measurement we cannot observe the system **S** by itself, but must instead investigate the system **S+M,** in order to obtain (numerically) its interaction with the measuring apparatus **M**. The theory of the measurement is a statement concerning **S+M**, and should describe how the state of **S** is related to certain properties of the state of **M**". (Ibidem: 352)

Dirac's and von Neumann's introduction of MIC would give birth to the dynamical core of OQM by introducing a postulate ruling a radically different sort of evolution for the quantum state when a measurement process takes place. This reveals that quantum mechanics is somehow a twofaced theory, which manifests in the fact that the bare QM solely involves a unitary, deterministic, smooth and linear evolution given by a Schrödinger-type equation, whereas OQM adds a non-unitary, purely probabilistic, sharp and non-liner evolution given by a particular physical process that collapses the quantum state into an eigenstates of some observable. Let's put all this more formally.

Suppose an electron entering a *z*-device that measures *z*-spin's electron. According to QM, once the electron is correlated with the *z*-device, what we ended up with is a chain of superpositions like

$$|\psi(t_1)\rangle_z = \sqrt{\frac{1}{2}}(|\uparrow\rangle_z|"z\ up"\rangle^D + |\downarrow\rangle_z|"z\ down"\rangle^D) \quad (1)$$

What Dirac's and von Neumann's postulate tells us is that, during a *z*-spin measurements, the quantum state in eq. 1 abruptly and suddenly collapses with a fifteen percent of chances into either $|\uparrow\rangle_z|"z\ up"\rangle^D$ or $|\downarrow\rangle_z|"z\ down"\rangle^D$. Otherwise state, the quantum state "jumps"[1] into one of its eigenstates, undergoing a radically different sort of evolution –a non-unitary, non-deterministic and non-linear one. In this way, we obtain an explanation of why we observe what we actually observe after measurements.

From above, it is evident that in OQM measurements play a crucial role in detailing the quantum evolution. After all quantum-mechanical results and predictions are about quantum systems *and* measurement devices (as von Neumann stresses). So, even though the Schrödinger equation correctly describes the evolution of any quantum state in isolation, this is unimportant (von Neumann 1955: 357) from the quantum mechanics' complete viewpoint: the theory, as long as it involves *measurements*, must also provide some explanations of why if a quantum state was

[1] The "jumps" or "state-vector collapses" have been understood in different ways. Physicists like John von Neumann and Eugene Wigner thought that collapses were physically real processes that occurred under the presence of an observer's counciousnes (von Neumann 1955) and, as in the case of Wigner, at the level of counciousnes (Wigner 1967: 171). This view was not completely shared by Heisenberg, who believed that humans were not necessary involved in the measurement process. It rather involves, essentially, an interaction between the measured system and the rest of the world (Heisenberg 1958: 54-55).

evolving in a superposition of states, it suddenly and rapidly *collapses* into one of its eigenstates when measured. MIC is supposed to explain it by extending the list of axioms (or postulates) of QM.

When it comes to specify OQM conceptually, some problems arise as the interpretation was supported by a huge variety of physicists and philosophers holding quite divergent principles and philosophies. For instance, OQM has been typically bound to the so-called *Copenhagen Interpretation*. But this relation was never entirely clear: There is no single clear statement of what the Copenhagen interpretation is, so it is not an easy task to clearly single its main tenets out. An explanation for this is that the interpretation has involved many philosophers and physicists endorsing unalike ideas, so that it ends up being an amalgam of unclear and loosely related tenets. Furthermore, the interpretation is frequently associated with Niels Bohr's own ideas (its first and main defender), though it is not at all clear either what Bohr's ideas exactly were. For instance, Bohr never talked about "the collapse of the wave function" (if the wave-function is not real for him, how could it collapse?), whereas Heisenberg did. Notwithstanding, OQM's and Copenhagen's seem to have in general followed Heisenberg's ideas on this, rather Bohr's.

Yet, despite these unclarities and interpretational issues, there are at least some central tenets endorsed by virtually any OQM's supporters (including Copenhagen's). All this has been largely discussed in the literature and a careful analysis of these issues would take us far beyond the scopes of this paper (see Cushing 1994, Brock 2003, Aaserud and Heilbron 2013, and Faye 1991, 2014 for details). But it is worth mentioning, and emphasizing, two ideas that have pervaded OQM and have a "Copenhagen air":

- the inner nature of the quantum realm remains veiled to what we are able *to know* and *communicate*: the quantum theory can only be about measurement outcomes (see, for instance, Bohr 1935: 1025, Zeilinger 2005: 743).

- Any meaningful sense of reality (and thus of ontology) can only concern what is knowable by (classical) experiments and communicated by our (classical) language. This likely just expresses a pragmatic Kantian stance sponsored by Bohr (Brock 2003, Faye 2014), though it has been often interpreted as a manifested *instrumentalist* (or *anti-realist*) posture with respect to quantum theory (mainly to the wave-function).

For my concerns in this paper, these tenets point to one clear direction: whatever an arrow of time comes to be within OQM, measurements (and the type of evolution they rule) will play a paramount role, both theoretically and conceptually.

3. Measurement-Induced Collapses and the Arrow of Time

By assuming OQM, the question of whether QM exhibits a time's direction becomes whether OQM does it. And this implies to evaluate whether OQM involves some time asymmetric element among its tenets that lay the foundations for an arrow of time. As I mentioned above, it has been argued that OQM effectively provides us with the required elements to stablish a quantum arrow of time. This claim has come up in various places (it appears, for instance, in Aharanov's critic 1964 paper as an already widely-extended belief. See also, for instance, Popper 1982, Penrose 1989, Price 1996, Arntzenius 1997, Lucas 1999, Healey 2002, Atkinson 2006, Ellis 2013, Callender 2018: 94 and references therein). For instance, Frank Arntzenius (1997) has defended that collapse theories introduce an arrow of time since

> "such theories say that are invariant forward transition chances for each of the possible initial quantum state to the possible collapsed states after the interaction (…). One cannot add some set of invariant backward transition chances to such theories, while retaining an empirically adequate theory, since the backward transition frequencies in the phenomena are highly non-invariant when one varies the frequencies with which the photons are emitted from the possible sources (1997: S218)

For David Atkinson, the time asymmetry in OQM (in a more Copenhagen guise) comes actually from 'observation' (Atkinson 2006: 540). In any case, a collapse-induced time asymmetry has been probably popularized within the philosophy of physics field by Roger Penrose (1989) and a quite simple thought experiment. This is a good starting point to assess the proposal, but, before getting into it, I will briefly distinguish two senses in which we can speak of an arrow of time –a *structural* and a *non-structural* sense.

3.1. Structural and non-structural arrows of time.

One of the main issues concerning the metaphysics of time involves the origin and nature of the distinction between the past-to-future and the future-to-past direction. Such a distinction has been usually referred to as "arrows of time". Many arrows of time can be found in physics as the pervasive increase of entropy, phenomena involving radiation, various decay processes, and so forth. The existence of such arrows is out of any doubt. The philosophical problem, though, is twofold. First, what is the relation among different arrows of time? Second, is there a *fundamental* or *structural* arrow of time? I will focus my attention to this latter question.

Though the existence of various arrows of time in physics is recognized, it is also claimed that none of them can be considered as *structural*. The reasons for this are multiple, but they overall boil down to the fact the fundamental dynamical equations of our best physical theories (i.e. those equation describing free systems under the influence of no force or of a constant field) are time-reversal symmetric. This means that they remain invariant under the action of reversing the direction of time in them. In this sense, it is said that the wide panoply of temporally asymmetric phenomena we find in nature somehow *emerge* from such a directionless fundamental level. A clear instance of this is the case of thermodynamic processes and their underlying classical-mechanical basis –even though entropy irremediably increases in isolated thermodynamics systems towards the future, the underlying mechanics remains invariant under the inversion of the direction of time. Therefore, the temporal asymmetry at the thermodynamics level remains at some degree unexplained by the mechanical basis. The same issue replicates across different theories. In virtue of this, it has been considered that the problem of the arrow of time in physics is to provide an explanation of how temporally asymmetric phenomena can emerge from a temporal symmetric dynamic (i.e., from time-reversal symmetric dynamical laws).

It is however useful to properly qualify the different arrows of time. There seems to be a sense conforming to which an arrow of time can be more fundamental (or structural) than others. Paul Horwich, for instance, claims that such an arrow of time would be given by intrinsic properties of a theory's dynamics, which he relates to its capacity to remain invariant under time reversal. The idea is that a structural arrow of time is *built in* a theory's dynamics, in the sense that a it is the very dynamics which exhibits an asymmetry of time itself and it does not depend on any external property or element. In this sense, the arrow of time is *intrinsic* to the dynamics, since its time-reversal asymmetry is a property thereof. The argument probably relies on the relation between a dynamic's theory and its underlying space-time geometry –if a theory's dynamics is time-reversal symmetric, it would reveal an intrinsic asymmetry in the structure of the space-time posed by the theory (see, for instance, North 2008). In general, defenders of non-reductionist accounts of the arrow of time have defended that a structural arrow of time, if it exists, it will be given by an intrinsic property of the space-time (see Earman 1974, Maudlin 2002), or a theory's dynamics (Horwich 1987). Time-reversal (a)symmetry will simply make such a feature dynamically evident.

Notwithstanding, reductionist accounts of the arrow of time have greatly assumed that the existence of time-reversal symmetric dynamical equations play some role in our understanding of time's direction in physics, but in a different sense –they hamper a structural arrow of time. In general, those views have explained the arrows of time in terms of properties or elements external to the dynamics. The paradigmatic case is the relying on special initial conditions –*even though* a theory's dynamics is invariant under time reversal (meaning that there seems not to involve a structural distinction between time's directions), temporal asymmetries emerge from special initial conditions, for instance, an incredibly low entropy initial state. This sense of arrow of time seems to be more circumscribed in many senses, but it is clear that it does not come out solely from the dynamic, but it needs to be imposed through external properties or elements.

A deeper analysis of the grounds for such distinction will surely require further argumentation. But it is enough for the purposes of this paper to leave clear that there seems to be a distinction between a structural arrow of time and non-structural (or emergent) arrows of time. I think the difference can be unfolded in different ways, but it crucially hinges upon which resources a theory's dynamics has to draw the distinction between the past-to-future and the future-to-past directions. An easy way to see all this is through the models of a theory and in which sense they are time-reversal symmetric.

Suppose a physical theory T, whose models can be portioned in two classes: those with t increasing (W_f) and those with t decreasing (W_b). So, W_f will include all those evolutions going in the forward direction of time, and W_b those going backward. If a theory's dynamics is time-reversal symmetric, then it will produce a pair of time-symmetric twins as models, that is, W_f and W_b. Furthermore, a mapping between models can be easily implemented. But, if a theory's dynamics turns out asymmetric under time reversal, then its dynamics will only generate either W_f-type models or W_b-type ones. So, intrinsic properties of a theory's dynamics (in Horwich's sense) rules out a complete class of possible evolutions. The situation is quite different for non-structural or emergent arrows of time. To begin, we are dealing with a theory's dynamics that generates both W_f-type and W_b-type models. In this sense, there is no (structural) arrow of time. However, a singular model can exhibit an asymmetry with respect to some element in it. For instance, the initial conditions of a particular model are so special that generate an (non-structural or emergent) arrow of time, which is only valid within such a model. Such an arrow of time thus depends on the special properties of the model, which are external to the theory's dynamics.

To sum up. In the rest of the sections, I will refer to a structural or non-structural arrow of time in the aforementioned sense. A structural arrow of time is solely given by a theory's dynamics. Oppositely, a non-structural arrow of time is not given by a theory's dynamics, but it heavily depends on external properties or elements.

3.2. Time asymmetry and Measurements –Penrose's thought experiment

Let us now take a closer look at the idea that MIC bases a quantum arrow of time. As I previously mentioned, Penrose put forward a simple thought experiment to illustrate it.

Penrose starts by recognizing that OQM is in fact a time-symmetric theory but only regarding the part involving the Schrödinger equation –its *unitary part* (1989: 354). As for the other, its *non-unitary part* given by MIC, the theory turns out to be time *a*symmetric. To see it, imagine the following setup. Suppose a lamp *L* at one extreme of the experimental arrangement, and a photo-detector *P* at the opposite extreme. Between them, a half-silvered mirror *M* is placed, which is tilted at a 45° angle to the line from *L* to *P*. Suppose now that *L* randomly emits a photon, which is aimed at *P* to be detected. At *L*, some device registers with high reliability the number of photons emitted given a time interval.

When a photon is emitted by *L*, the half-silvered mirror *M* can either reflects it or letting it to pass through. Thinking of the experiment in quantum-mechanical terms, Penrose suggests that when a single photon is emitted, the photon's wave-function "impacts" the half-silvered mirror and splits in two parts: one part is reflected with an amplitude of $\sqrt{1/2}$ and the other passes through with the same amplitude. Until an observation is eventually made, both parts of the photon's wave-function –Penrose stresses– must be considered as "co-existing" in the *forward*-time direction.

Through the statistical postulate of QM, we know that the probability that the photon reaches the photo-cell *P* is given by the square of the moduli of the amplitude, $|\sqrt{1/2}|^2 = 1/2$. Quantum mechanical calculations thus allow easily answering the following question: "Given that *L* registers, what is the probability that *P* registers?" OQM (as well as QM) implies that the probability is exactly 'one-half'. And, after running the experiment many times, we will get (approximately) that probability distribution. We can also infer straightforwardly that *if P* didn't register, then the photon hit the mirror and bounced off toward the laboratory wall (point *A*).

It has been assumed though that time was running forward: the photon *was* firstly emitted by *L*, *after* a while reached the half-silvered mirror *M*, and *then* it split in two parts. At the (*future)* end of the experiment, the photon either reached the laboratory wall or was registered by the photo-cell. For all practical purposes, OQM has predicted the results wonderfully well. But, in order to know if OQM is time symmetric, we have to consider if it yields the same results (that is, if it yields the same probability distribution) if time run *backward*. To find it out, Penrose claims we should rather begin with the following (time-reversed) question: "Given that *P* registers, what is the probability that *L* registers?"

Penrose says: "we note that the *correct* experiment answer to this question is not 'one-half' at all, but 'one'" (1989: 358), for if the photo-cell *P* indeed registers, then it is virtually certain that the photon was emitted (and thereby registered) by *L*. So, whenever *P* registers it logically follows that *L* also registered the 100% of times. This is not however what a time-reversed version of OQM retrodicts. It rather retrodicts that if we trace backward in time the photon's wave-function that reached *P*, then it will have one-half of probability of reaching *L*, and one-half of being reflected and of hitting the laboratory wall at a point *B* (the opposite to *A*). In the light of this, Penrose claims that "in the case of our time-reversed question, the quantum-mechanical calculation has given us *completely the wrong answer*" (1989: 358. Italics in the original).

The upshot of all this is that OQM does *not* gives us the *same* predictions/retrodictions in both directions of time. Hence, OQM implies an asymmetry between predictions and retrodictions. This asymmetry would be symptomatic of the fact that OQM treats the past-to-future direction and the future-to-past direction differently. Penrose puts it as following. "If we wish to calculate the probability of a past state on the basis of a known future state, we get quite the wrong answers if we try to adopt the standard R [MIC] procedure" (1989: 359). To put it simply, the class of models that OQM generates are asymmetric with respect to the class of models that *T*(OQM) –the time-reversed version of OQM– generates. Importantly, only those models generated by OQM turn out to be empirically adequate. And what does the job is the essential assumption that MIC is intrinsically time-reversal asymmetric.

George Ellis (2013) has put forward a more general argument to show the time-asymmetric nature of MIC. Ellis' rationale is mainly based on the fact the quantum states may collapse (when measured), but they never "*un*collapse". The process is intrinsically time-asymmetric to the extent to which the eigenstate $|q_k\rangle$ occurs *after* measuring (i.e. collapsing), that is, *after* the superposition. Furthermore, all coefficients in the superposition states we started with have been lost, so the knowledge of the final state says *nothing* about the initial state. To conclude, in Ellis' words, "the process [MIC] is where the time irreversibility, and hence the arrow of time, is manifested at the quantum level" (2013: 243).

Huw Price (1996) makes the same case in affirming that any measurement process would, under certain assumptions, introduce an "objective asymmetry in the structure of reality" (1996: 207). Assuming OQM, the state of a quantum system in the period between two measurements reflects the nature of the former instead of the latter. Specifically, if an electron in a superposed state of the observable position is localized by means of a measurement device, then it will unitarily evolve according to the Schrödinger equation and its state will reflect the fact that the electron *was measured* and *localized* by a position-device. If we measure at a later time the electron's momentum with a momentum-device, electron's state will not reflect the nature of the second measurement (lying in its future) but that of former (lying in its past).

When the situation between two measurements is time-reversed, the result is oddly the contrary. What we would then see, according to Price, is the electron's state evolving toward a state associated with a measurement device in which it is to be involved in the future (1996: 206). OQM, and MIC consequently, typically takes for granted that a quantum system's state depends upon its past state and its past interactions. The fact that things look so weird when running in the backward direction of time would indicate that a deep time-asymmetry lies at the core of MIC.

To sum up. In introducing an additional dynamical postulate, OQM by the same maneuver introduces a time-asymmetric ingredient in the quantum theory. Such an asymmetry comes out from the very principles of the theory and it is built in its dynamics. So, we could on firm basis hold that OQM allows defending a *structural quantum* arrow of time. In a nutshell, the thesis is that MIC turns out to be a non-time-reversal invariant law of the theory to the extent that

- OQM does not provides the same probability predictions in both directions of time, and
- quantum systems always collapse when measured but never “uncollapse”, according to MIC.

To put it in the vocabulary of the Section 2.1, the structure of OQM’s solutions is *asymmetric* under time reversal since the set of its *empirically adequate* models is given by either $W = W^f$ or $W = W^b$. In W^b we should include evolutions giving us the wrong probability predictions and those quantum systems “uncollapsing” when temporally reversed. These are disregarded by the same MIC’s mechanism and by the quantum-mechanical statistic we expect to get.

To see it clearly, let us take Penrose’s thought experiment again. Whereas the QM algorithm predicts in, say, the future direction of time that probability of registering a photon in *P* is one-half agreeing on what we observe, the time-reversed algorithm predicts that probability should also be one-half, when *logically* follows that it would rather be one. In this way, we are entitled to get rid of one set of solutions (those predicting a result that is *a priori* wrong). Consequently, what explains why OQM provides a structural arrow of time is that it turns out to be a predictive but not a *retrodictive* theory. And In virtue of this, it does treat the past-to-future direction and the future-to-past direction differently It is worth emphasizing that this result is independent of whether the Schrödinger equation is time-reversal invariant or not.

4. Arguments against a MIC-based arrow of time

In this section, I will critically analyze a MIC-based arrow of time as well as some of the arguments against it. In the end, the conclusion will be that a MIC-based arrow of time might at best be local and non-structural.

We can regard a MIC-based arrow of time as supported by two pillars:

(a) MIC is *genuinely* a time asymmetric postulate. That it, MIC turns out time asymmetric under reliable time-reversal transformation.

(b) MIC introduces a temporal asymmetry in the theory that yields a structural arrow of time

The proposal of a MIC-based arrow of time has been already criticized elsewhere. In particular, Craig Callender (2000) and Steven Savitt (1996) have claimed that the time-reversal operation upon which a MIC-based arrow of time relies is misconceived. So, they argue, under a more adequate time-reversal transformation, OQM comes out time symmetric, and thereby, any quantum arrow of time fades away. In the line of the above-mentioned pillars, there would be at least two strategies to puncture the MIC-based proposal:

(a) To argument that MIC is not genuinely *time asymmetric.*
(b) To claim that, though temporally asymmetric, MIC does not introduce a *structural* time asymmetry.

Through the first strategy, it is argued that the way in which time has been reversed is misconceived. Hence, MIC, and thereby OQM, is not genuinely time asymmetric. This is the path followed by Callender and Savitt. Through the second, it is taken for granted that MIC is temporally asymmetric, but it is held that such an asymmetry is non-structural and local.

4.1. OQM is not genuinely time asymmetric

There are two senses in which Penrose's thought experiment results a bit confusing in showing that MIC introduces a genuine and interesting time asymmetry.

First of all, Penrose uses extra-quantum mechanical information when judging whether the theory is time symmetric[2]. In particular, in replying the forward-in-time answer "Given that *L* registers, what is the probability that *P* registers?" Penrose appeals to the usual quantum-mechanical expectations. But, in considering the time-reversed answer "Given that *P* registers, what is the probability that *L* registers?" Penrose rather appeals to the non-quantum mechanical answer 'one' judged as "the *correct* experimental answer" (Penrose 1989: 358). This seems not to be a fair movement.

To begin with, the experiment cannot be actually carried out *in the backward* direction of time, so we have *to* instead *imagine* what we would expect of so-settled experiment *if* the direction of time were reversed. But, in imagining such time-reversed scenario, Penrose leaks non-quantum mechanical information when judging what would be the right answer. Clearly, the (backward)

[2] Craig Callender (2000) has also mentioned an akin point, though he does not develop it.

quantum-mechanical answer is that one would obtain one-half of chances of getting the electron registered at L, which is equal to that obtained in the original direction of time (that is, through the *forward-in-time-oriented* OQM). But such a result would be quite shocking, and somehow anti-intuitive for Penrose, because we *already know* that L always registers, so that the *correct* prediction would seem to be 'one' rather than 'one-half'. But where does such a knowledge come from? It comes from running the experiment in the original direction of time and from extra-quantum mechanical information extracted from how the experiment was settled in the future-headed direction of time. Therefore, this asymmetry cannot be genuine or interesting since it is grounded in temporally biased knowledge.

The second sense in which Penrose's argument could be confusing relates to how time is being inverted in Penrose's thought experiment. The notion of time reversal is generally applied to differential dynamical equations. So, we have a relatively sharp receipt of how differential dynamical equations should be temporally reversed[3]. But, now, we are dealing with a much worldlier situation involving photocells or lamps emitting photons. And we are left a bit clueless about what a time-reversed experimental setup would look like.

What Penrose basically does in his thought experiment to reverse time is to imagine the same objects and the same situation but in the reverse order. Let us call Penrose's time-reversal transformation T^P. So, given the (relevant) sequence where the photon is emitted by the lamp L, hits the half-silvered mirror M, passes through it and reaches the photo-cell P

Future-headed sequence $L \to M \to P$

T^P produces the (allegedly) time-reversed sequence

Past-headed sequence $T^P(L \to M \to P) = P \to M \to L$

The question that the quantum-mechanical algorithm has to respond must be temporally reversed accordingly. By simply inverting the sequence as shown above, we have to also interchange the terms in the question, as Penrose indeed does: "Given that L registers, what is the probability that

[3] This claim should be tempered though. We have a relatively sharp recipe of how time reversal should be formally implemented *in abstract*, but when it comes to details or concrete instantiations, some problems come up even in such an abstract level. For discussion, see Sachs 1987, Albert 2000, Callender 2000, Roberts 2017, Lopez 2019).

P registers?" turns into the time-reversed question "Given that *P* registers, what is the probability that *L* registers?"

It is clear in which sense OQM is time asymmetric *if* MIC and T^P hold. However, it remains to be seen whether T^P is a tenable time-reversal transformation. If it is not, then the time asymmetry in Penrose's thought experiment may be put into question. Indeed, Penrose does not discuss any other alternative, but he uncritically assumes that an inversion of the direction of time amounts to simply inverting the state sequence and then to working out the corresponding probabilities (assuming extra-quantum mechanical information as was shown before). Yet, there are some other alternatives to take into account. For instance, Savitt defines at least three very broad notions of time reversal in the literature: (i) *time-reversal$_1$*, which amounts to the mapping $T: t \rightarrow -t$; (ii) *time-reversal$_2$*, which not only maps $t \rightarrow -t$ but also temporally reverses the very *states* (and *objects*) of a sequence; and (iii) *time-reversal$_3$*, which captures the essential idea that time reversal is motion reversal, and thereby, it must retrace the physical system's trajectory.

Interestingly, Penrose's thought experiment is non-time-reversal invariant only under the first sense of time reversal but is time-reversal invariant in the second and third senses. In the same vein, Callender asks: "why compare $P(S_i \rightarrow S_f)$ with $P\ (S_f \rightarrow S_i)$ and not with $P\ (S_f^T \rightarrow S_i^T)$?" (2000: 256). What Callender finds suspicious is that T^P does not transform the states themselves but leaves them as they were in the direction of time we started with. So, Callender claims that is time-reversal invariance$_2$ what actually amounts to reversing the direction of time properly, and not time-reversal invariance$_1$, as Penrose presupposes. Hence, the genuine time-reversed sequence of Penrose's thought experiment is not given by T^P but by Callender's time-reversal transformation, T^C:

Past-headed sequence $$T^C(L \rightarrow M \rightarrow P) = P^T \rightarrow M^T \rightarrow L^T$$

where X^T is a time-reversed state or object in the sequence. Callender gives some hints about how this should be interpreted. He says: "if Penrose is genuinely concerned with TRI [time-reversal invariance], he should treat the *emitter as a receiver* and *vice versa*" (2000: 256. Emphasis added). Therefore, the right time-reversed question to make to the quantum-mechanical algorithm is not "what is the probability that *L* registers, given that *P* registers", but "what is the probability that a *time-reversed L* registers, given that a *time-reversed P* registers". Penrose would thus be addressing his own thought experiment from the wrong angle when time reversed. And when addressed rightly, time-symmetry (in particular, T^C-symmetry) is restored.

Let me add some comments on this. It is true that T^P is not the only conceivable time-reversal transformation. Furthermore, it might be not the most adequate implementation of time reversal. Callender and Savitt are right at pointing to this, compelling any defender of Penrose's argument to provide some support for T^P. That is fair and further justification should be given. However, I disagree on Callender's conclusion that T^C be the right implementation of time reversal for Penrose's thought experiment. I think his argument is flawed in two ways. First, it does not offer a more reliable way to time reverse Penrose's thought experiment. Instead of that, it leads to *destroy* the very objects involved in the thought experiment. Second, it begs the question if used to claim that time symmetry holds. These issues follow from two possible readings of Callender's proposal of time reversal, particularly, of how the states in the series must be temporally reversed.

Let us suppose that T^C is the right way to temporally reverse Penrose's thought experiment. As Callender suggests, it implies that one should treat the emitter as receiver and vice versa. Callender does not add much to this but let us to parse it out. To begin, T^C implies that,

$$T^C(emitter) = receiver \tag{2}$$

It means that a time-reversed photocell should be treated as an emitter. Thus, the time-reversed sequence

$$T^C(L \rightarrow M \rightarrow P) = P^T \rightarrow M^T \rightarrow L^T \tag{3}$$

should be instead read saying that a time-reversed photocell emits a photon at t_2 and shortly after the time-reversed photon hits the time-reversed mirror, always with *t* decreasing. Through the quantum-mechanical algorithm, we know that it has one-half chances of passing through the half-silvered mirrored and of reaching the time-reversed lamp, and one-half of being headed to the laboratory wall. As it was mentioned previously, if Penrose's though experiment is so time reversed, then it comes out time-reversal invariant as it delivers the same probabilities for *t* increasing and *t* decreasing.

At this point, the following question can be raised: how would a time-reversed photo-cell work? We know how photocells works in the ordinary direction of time, but we have no clue about how a time-reversed photocell would work. Treating the photocell as an *emitter* doesn't help so much for a photocell is not the sort of thing that emits anything. Why are we entitled to suppose that a photocell will behave in a completely different way, capable of emitting electrons and behaving as an emitter when temporally reversed?

It can be argued that ordinary photocells do not emit anything, but time-reversed photocells do it. In reply to this, it can be said that in fact a time-reversed *something* is obtained, but it does not deserve the name of 'photo-cell'. And this is so because it simply does not work like a photocell. It seems, hence, that by T^C reversing the direction of time the very objects (or states) involved in the sequence are destroyed. Photocells, if we wish to use the word meaningfully, cannot be the sort of thing that emits anything in *either* direction of time in so far as we are still dealing with photocells in some relevant sense.

Let me put the point slightly differently. Photocells may come in various types and instantiate different properties, so we can imagine different modal scenarios for photocells, altering their properties and their conditions. Notwithstanding, if we wish to still refer to photo-cells properly, a certain sub-group of properties must remain fixed and some other properties must be necessarily excluded. Otherwise, we would be unable to identify the objects at issue through different scenarios. My claim is that the property of "functioning like a photo-cell" (that is, the more general property of "behaving as a receiver") must remain fixed. Conversely, the property of "behaving like an emitter" must be excluded. All this in order to identify photocells thought different scenarios and to keep talking about photocells meaningfully.

I do not see any reason why this should be different in a time-reversed scenario. A time-reversed photocell in a past-headed experimental running should emit nothing to the same extent that a photocell emits nothing in a future-headed experimental running. Otherwise, Otherwise, we are referring to a different object, no longer a photocell. But, in fact, it would be strange that the very functional nature of the objects changes so radically when time is reversed –I see no time-dependent feature in the functional nature of a photo-cell that required a change if time were reversed. Quite the opposite, if object's inner nature can freely vary when time reversed, then time-reversal invariance will practically always follow trivially.

And this is how the second reading of the argument comes into play: we should make explicit how a photocell transforms into a different sort of object under time reversal. I think that the only possible choice is to suppose that

$$T^C(P) = L \tag{4}$$

That is, a time-reversed photocell should be treated *as if* it were a lamp. Analogously,

$$T^C(L) = P \tag{5}$$

Now it seems we are getting somewhere for a lamp is in fact the sort of thing that is able to behave like an emitter. This could be reworded as following: when an experiment is T^C-reversed, the time-reversed photocell is capable of emitting because it *is*, in the opposite direction of time, a lamp. This reading, however, is patently question-begging. What is at issue is to test whether time symmetry holds, but if time symmetry can transform the objects (and their state) at will, then it seems that the transformation is designed to leave the experimental setup virtually unaltered. So, both situations are bound to be time-reversal symmetric because the transformation does nothing if a time-reversed photo-cell behaves like a lamp, and a time-reversed lamp behaves like a photo-cell: we are simply swapping names and keeping the same physical situation unaltered.

To put it more drastically: we are simply marking the states with a "^{T}". And it is blatant that a graphical mark will not produce any physical change! The problem with this implementation is that implicitly assumes that a change in the direction of time is, so to speak, *innocuous* in the description of any physical situation. It just plays the role of re-parametrizing the time coordinate, of swapping names and of leaving the experimental setup as unaltered as possible. This is not per se a wrong-headed implementation of time reversal. But I do not see how a substantive philosophical claim may come out from it. After all, we are dealing with a transformation that will surely produce time symmetric scenarios.

To sum up. Many of these criticisms are on the right track in pointing that Penrose's time-reversal transformation requires further justification. They are also on the right track in pointing to the fact that there are other candidates that might do the job. Remarkably, Penrose's time asymmetric experiment may come out time symmetric under a different implementation of time reversal. However, I think we should be cautious since the other candidates also run into troubles when implemented. So, at this point, I believe the best we can do is to affirm that whether the time asymmetry of Penrose's though experiment is interesting or genuine largely depends upon the time reversal implementation. I do not have a good answer for it. To a good extent, I think that the implementation of time reversal hinges crucially upon previously assumed philosophical commitments that have to be unpacked case by case. In some sense, given the right philosophical framework, any time-reversal transformation might be defendable.

Given this scenario, a noteworthy path is the following. Let us assume that OQM is time asymmetric as Penrose argues it is. Instead of questioning that, let us look into the qualification of such a claim. What sort of time asymmetry, and arrow of time, does OQM deliver?

4.2. A MIC-based arrow of time: local and non-structural.

Let's tackle Penrose's argument from a different angle. Remember that the statistical postulate of the theory assumes that if a measurement of the observable A is carried out, it will produce, with a certain probability, one of its eigenvalues a_i as a result. So, if a system is in the state $|\psi\rangle = \sum a_i |a_i\rangle$, then the probability that the eigenvalue a_i of A is found when measured is equal to $P(A = a_i, |\psi\rangle) = |a_i|^2$. In its logical form, the algorithm says

FORWARD $P(measure\ at\ t_2\ value\ a_i\ of\ observable\ A, |\psi\rangle\ at\ t_1) = p$

Borrowing Albert's words, the crucial question here is whether this algorithm (giving us the conditional probabilities of some *later* state given an *earlier* state) when formulated backward works equally well as FORWARD

BACKWARD $P(measure\ at\ t_0\ value\ a_i\ of\ observable\ A, |\psi\rangle\ at\ t_1) = p$

It is a fact that OQM does not give us the probability of earlier states given later states for the theory is predictive, but not retrodictive (see Callender 2000: 258). Something like this was probably in Penrose's mind in drawing his thought experiment up. If this is the case, he was right all along in regarding OQM as a time *a*symmetric theory since the theory is not indeed retrodictive. And this fact is independent of the time-reversal transformation we employ. Satosi Watanabe has also subscribed this conclusion in claiming that "it is precisely irretrodictability what is related to phenomenal one-wayness" (1965: 56)[4]. Hence, MIC inevitably breaks the time-reversal symmetry of the unitary part of the theory since it yields results directly in terms of conditional probabilities for states in the future, but not in the past[5].

The point I want to make here is that even though MIC introduces a time asymmetry in the theory, it falls short in grounding a global, structural arrow of time. I will put forward two arguments. I will show that MIC can be only defined locally since it cannot be applied to the universe as a whole. In consequence, any arrow of time it yields will be *local*. Second, I will argue that any MIC-based arrow of time necessarily relies upon extrinsic properties of the dynamics for the time asymmetry to make sense.

Let's start with the first argument. As many times repeated, OQM assigns a fundamental role to measurements, and thereby, to the *sort of* measurement performed –as von Neumann said, the quantum theory is about the measured system *plus* the measuring apparatus. It follows from this that any temporal MIC-based asymmetry makes sense *only if* an external measurement device can be suitably defined, which requires the system to be open. So, any definition of MIC and the resultant arrow of time makes sense only if the system interacts with an external apparatus. However, this is not possible if we take the quantum state of the universe as a whole –by definition, the universe is a closed system, so it is not possible to suitably define a measurement device out of the universe. But if the experimental situation cannot be defined, neither can MIC. Therefore, any MIC-based arrow of time will necessarily be local as well.

We can take a step further. It could be argued that in OQM the wave-function of the entire universe[6] never collapses but always evolves unitarily according to some universal Schrödinger-

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[4] Even though it's true that in general time asymmetry (or non-time-reversal invariance) and "irretrodictability" may come to be thought as two quite different properties, and one could consequently argue that no temporal directionality should be followed from irretrodictability, it has been argued that in some cases, like non-relativistic quantum mechanics, the implication is right. Earman for instance claims that in any statistical theory non-time-reversal invariance directly follows from irretrodictability in the sense of BACKWARD (Earman 1974).

[5] We could think that by adding BACKWARD to the theory the problem vanishes. Richard Healey has showed that this cannot be done without trivializing the theory, if it is statistical. For further details and discussion about it, see Healey (1981: 103-108).

[6] It could be argued that the notion of a 'universal wave-function' makes no sense within OQM. It may be true. Nonetheless, it just imposes a more radical constraint over OQM, ruling out any global time asymmetry from the very outset. Thanks to Carl Hoefer for pointing this out.

type equation. In a nutshell, nothing can interrupt the unitary, linear and deterministic evolution of the universal wave function, if a measurement cannot be carried out. But, under the usual assumption that the Schrödinger equation is time-reversal symmetric, all this entails that the universe as a whole does not exhibit any arrow of time. And this scenario delivers a shattered picture of reality, as that presented in Section 2.1. On the one hand, there is a time symmetric universal quantum state. On the other, time asymmetric local quantum states within measurement contexts. This scenario, though coherent, is a bit puzzling. Yet, it emphasizes that OQM renders at best a local arrow of time.

The second argument concerns MIC itself. The point I want to make is that the transition "uncollapsed states" → "collapsed states" remains vague and undefined *as long as* the measuring device is not exhaustively specified. Therefore, any MIC-based arrow of time heavily relies upon our epistemic access to the information about a measurement context. It implies that any MIC-based arrow of time can be hardly regarded as *structural* since it does not strictly depend solely on intrinsic properties of OQM's dynamics, but also on the information we have about external factors intervening upon the dynamics.

The slogan of the proposal is to claim that the non-unitary transition caused by MIC would allow defining a direction of time because the transition always goes from "uncollapsed/undefined states" to "collapsed/defined states". As it stands, however, this is not quite accurate in so much as the theory *also* describes the transition from "collapsed/defined states" to "uncollapsed/defined states" –for instance, when a quantum system is prepared in *a different basis.* To rephrase it, the above-mentioned transition is true *only if* the quantum state is collapsed onto the a previously fixed basis. Yet, we can only come to know that if we previously have information about the measuring device.

Suppose that $|a_1\rangle,\ |a_2\rangle$ are the eigenstates of the observable *A*. Suppose also we design an *A*-device, which measures the observable *A*. We know that when measuring the observable *A* through an *A*-device, the quantum state will collapse onto either of its eigenstates. However, we also know by the bare QM that it is possible to write down the eigenstates of *A* in a different basis, say, *B* with which *A* does not commute. Hence, we can rewrite each eigenstate $|a_1\rangle$ as a superposition of *B*'s eigenstates, $|a_1\rangle = |b_1\rangle + |b_2\rangle$, and the eigenstate $|b_1\rangle$ as $|b_1\rangle = |a_1\rangle + |a_2\rangle$. And the same goes, mutatis mutandis, for $|a_2\rangle$ and $|b_2\rangle$.

The idea is that, *without any further specification* about the experimental setup will be run, the “uncollapsed state” → “collapsed state” transition

$$|b_1\rangle = \ |a_1\rangle + |a_2\rangle \rightarrow \ |a_2 \qquad (6)$$

Can be rightfully viewed as the “collapsed state” → “uncollapsed state” transition

$$|b_1\rangle \rightarrow \ |b_1\rangle + |b_2\rangle \qquad (7)$$

where $|a_2\rangle = |b_1\rangle + |b_2\rangle$. The system will then “uncollapse”, so to speak, when measured. This is the case, for instance, when the initial state is *prepared* before running an experiment in a given basis.

In this light, the asymmetric transition “uncollapsed state” → “collapsed state” can be univocally fixed only in relation to a previously detailed experimental situation. It follows that the transition is not *intrinsically* asymmetric (that is, it does not depend *exclusively* on intrinsic properties of its dynamics), but depends on the information we have about the sort of experiment to be run, which defines the basis in which the state is to be written down. Once this information is available, it is true that system will never uncollapse in *that* measurement context and *that* basis. But, if the eigenstates of the system are expressed in a different basis, and the experiment’s configuration is modified, the system may undergo a “collapsed state” → “collapsed state” transition. Consequently, MIC itself, and any philosophically substantive claim we can extract from it, remains undefined without specifying the measurement context adequately.

From these reasons, it is not clear to me that MIC provides us the grounds for a *structural*, or even an objective, arrow of time in OQM. Let me make the case in more epistemic terms. Suppose that the any information available to us is that a quantum state in a superposition of $|a_1\rangle + |a_2\rangle$ was measured by an unspecified measurement device (it could have been either a *A*-device or a *B*-device). Someone told us that the outcome was ‘a_2’ meaning that the quantum state may have collapsed into eigenstate $|a_2\rangle$. The MIC-based arrow of time proposal will say that $|a_1\rangle + |a_2\rangle$ came earlier because is an uncollapsed state, whereas $|a_2\rangle$ came later, after the measurement, because it is a collapsed state.

Nevertheless, we could know nothing about the measurement context, whether the measurement device was an *A*-device or a *B*-device. If it was an *A*-device, then it is possible to claim that the state collapsed into the eigenstate $|a_2\rangle$. And this in fact displays the right sort of temporal asymmetry we were after. But if we do not know it, we may rewrite the states in a *B*-basis, and then obtain an "uncollapsing" scenario. Naturally, if we know we are dealing with a *B*-device, it would be highly confusing to write the state down in a different basis. But this is exactly the point: all depends on what is the information available to us. In an ignorance situation, we could express the state in either of the bases and there would be no matter of fact to assert that what was obtained was either an "uncollapsed state" → "collapsed state" or a "collapsed state" → "uncollapsed state" transition. When the information about the measuring device becomes available, it is relatively easy to decide whether a collapsing or an uncollapsing scenario took place. But, in accepting this, any attempt to ground a *structural* MIC-based arrow of time rapidly vanishes since it would be relative to the (arbitrary) choice of a measurement device. And it is not obvious at all how this choice could be related to an asymmetry of time structurally.

5. Concluding Remarks

In this paper, I have critically analyzed a widely accepted proposal claiming that MIC lays the groundwork for an objective, structural arrow of time in OQM. After introducing the proposal in some detail, in Section 3.1 I have discussed some of criticisms it received, in particular, those considering that some of defenses of a MIC-based arrow of time employ a wrongheaded notion of time reversal. In Section 3.2, I have assumed that, despite those criticisms, there is a relevant sense in which MIC produces a time-reversal asymmetry within OQM. Nonetheless, I have argued that such an asymmetry is much more constrained than usually thought. In accordance to this, I have shown that any MIC-based arrow of time can only be local and non-structural for, first, it cannot be suitably defined for the entire universe, and second, it crucially depends on external information about the measuring device.

As it was pointed out in the introduction, MIC is just one of the members of collapse theory families. Despite being almost the orthodoxy within the physicists' community, OQM has lately been rather delegated among philosophers of physics. Much attention has been instead drawn towards different collapse models within the DRP, where collapses produce spontaneously and independently of measurements. Furthermore, it has been argued (see, for instance, Albert 2000 and Esfeld and Sachse 2007) that DRP (and in particular, GRW) does in fact provide the grounds for an objective and intrinsic arrow of time. The analysis of the relationship between DRP and a collapse-based arrow of time is left for future research.

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