

Remarks on the Direction of Time in Quantum Mechanics

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I argue that in the many worlds interpretation of quantum mechanics time has no fundamental direction. I further discuss a way to recover thermodynamics in this interpretation using decoherence theory (Zurek and Paz 1994). Albert's proposal to recover thermodynamics from the collapse theory of Ghirardi et al. (1986) is also considered.

1. Introduction. At face value the statistical frequencies obtained in quantum mechanical measurements exhibit time asymmetry in the sense that they invariably seem to depend on initial and not final states. As is well known this cannot be taken to imply that time has an objective direction (i.e., that the spacetime structure in the future direction of time is different from the past direction) for the simple reason (among many others) that the asymmetric frequencies are accurately produced also by theories with perfectly time symmetric dynamical laws (e.g., Aharonov and Vaidman's (1991) two-time theory, and Bohm's pilot wave theory).

However, in standard quantum mechanics (e.g., von Neumann's (1932) formulation) the time asymmetry of the frequencies is explained by appealing to the explicit time asymmetry of the collapse of the wave function. This can be seen in a measurement interaction as follows. In the course of time the interaction has the form

$$\left(\sum_i \lambda_i |\varphi_i\rangle \right) \otimes |\psi_0\rangle \rightarrow \sum_i \lambda_i |\varphi_i\rangle \otimes |\psi_i\rangle, \quad (1)$$

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where the $|\varphi_i\rangle$ are the states of the system and the $|\psi_i\rangle$ are the pointer states of the measuring apparatus. The system starts out at the initial time in a pure state and ends up at the final time in the mixed state:

$$\rho_s = \sum_i |\lambda_i|^2 |\varphi_i\rangle\langle\varphi_i|, \quad (2)$$

where the Born rule probabilities $|\lambda_i|^2$ are fixed by the initial and not final state. If there is a real collapse, then the time evolution is truly stochastic, and the collapse yields a time directed (pure-to-mixed) transition, where at the final time the system is actually in one of the pure states $|\varphi_i\rangle$, and the $|\lambda_i|^2$ correspond to the genuine probabilities of each of the possible trajectories of the system.

In a dynamical theory of the collapse, e. g., the GRW theory (Ghirardi, Rimini, and Weber 1986), the above time asymmetry is built into the equations of motion. The dynamics then become explicitly non-invariant under time reversal. Moreover, the GRW transition probabilities are non-invariant under various manipulations in the forward but presumably not in the backward direction of time. This has prompted many authors (e.g., Arntzenius 1997) to say that time may have an objective direction according to the GRW theory in so far as the dynamics is concerned. Von Neumann (1932, ch. 5) argued that the quantum collapse brings about also an increase in the quantum analogue of entropy $-k\text{Tr}\rho \ln \rho$, and that this should imply also the usual time asymmetry in thermodynamic evolutions, i.e. why thermodynamic systems are invariably observed to evolve from low to high entropy states.

In the *Many Worlds* Interpretation (MWI) (following Everett (1957), DeWitt and Graham (1973), and Deutsch (1985)) the question of the direction of time involves some conflicting intuitions. On the one hand the dynamical equation of motion (e.g., the Schrödinger equation in the non-relativistic case) of the universal wave function, which we take to be lawlike in the MWI, is completely deterministic and time reversal invariant, where by *time reversal invariance* it is meant that the dynamics is invariant under complex conjugation and temporal reflection. This means, taking for example the Schrödinger equation, that $\psi(x, t)$ is a solution if and only if $\psi^*(x, -t)$ is, for all ψ . As a matter of principle this definition exhausts the full empirical content of time symmetry in quantum mechanics, since the Born rule predictions invariably assign the same probabilities to ψ and ψ^* , and so we shall work with it. Anyway, this is the usual definition of time symmetry in quantum mechanics. And so in the MWI the overall dynamics of the universal wave function does not pick out a genuine direction of time. And this means that the time asymmetric frequencies in the case of both quantum and thermodynamic measurements

may be explained only by introducing some probabilistic assumptions about the distribution of initial conditions, as in classical statistical mechanics.

On the other hand, we will see that the pure-to-mixed transitions associated with the quantum collapse are explained in the MWI in terms of what seem to be time directed transitions along the histories of the worlds. In particular, in the MWI the time directed collapse of the wave function in measurement-like interactions takes place as a matter of fact at each world; in some sense a single collapse is replaced with many collapses. And so this presumably may be taken to support the view that a genuine direction of time is picked out by some form of a world-dependent dynamics.

In this paper I want to consider in more detail these two intuitions in the MWI. To set the stage I sketch in Section 2 one version of the MWI based on decoherence theory. The direction of time in the context of pure quantum mechanics is taken up in Section 3. Then, in Section 4, I consider very roughly one way in which the thermodynamic time asymmetry can also be recovered. This is based on models developed by Zurek and Paz (1994) in quantum decoherence theory. Finally (Section 4), I compare these results with an alternative proposal by Albert (2000, ch. 7) in the context of the GRW collapse theory.

2. Worlds and Decoherence. In many versions of the MWI (e.g., Saunders 1995; Vaidman 2002) the splitting of the worlds is defined by the process of *decoherence* of the wave function. In standard models of decoherence theory (e.g., Caldeira and Leggett 1983; Joos and Zeh 1985; Zurek, Habib, and Paz 1993; Zeh 1992) a macroscopic system interacts with an environment that has many degrees of freedom. It is assumed that the interaction depends on some preferred observable Π of the system (the eigenstates of which are called the *decohering variables*), so that the interaction Hamiltonian H_{int} commutes (approximately) with Π satisfying

$$[H_{int}, \Pi] \approx 0. \quad (3)$$

The initial state of system and environment is assumed to be approximately a product state

$$|\psi(x_1 \dots x_N, t)\rangle \otimes |E\rangle, \quad (4)$$

where $|\psi(x_1 \dots x_N, t)\rangle$ is some quantum state of the system and $|E\rangle$ is some initial state of the environment. This means, in particular, that the states of the system and of the environment are separable (i.e., not quantum mechanically entangled). The Schrödinger equation yields for this interaction the state:

$$|\Psi(t)\rangle = \sum_i \mu_i(t) |\psi_i\rangle \otimes |E_i(t)\rangle, \quad (5)$$

where the kets $|\psi_i\rangle$ are assumed to be the eigenstates of Π , and the $|E_i(t)\rangle$ are the *relative* states of the environment. In the standard models it is shown that the scalar products between different $|E_i(t)\rangle$ in (5) decay exponentially satisfying

$$\langle E_i(t + \Delta t) | E_j(t + \Delta t) \rangle \approx \delta_{ij} \quad (6)$$

after extremely short times Δt (called *decoherence times*). These times are typically short, around 10^{-23} sec.¹ It is further shown that (5) and (6) together imply that the reduced state of the system approaches the diagonal form:

$$\rho_s(t) \approx \sum_i |\psi_i\rangle |\mu_i(t)|^2 \langle \psi_i|, \quad (7)$$

within times comparable to Δt (so that formally the amplitude squared measure behaves like classical probability; see below). The approach of $\rho_s(t)$ to the diagonal form in (7) is highly invariant under changes of the initial state of the system and of the environment.

The standard models usually assume that (approximate) position picks out sets of preferred states in the Hilbert space of the system, or more generally that preferred sets of states are fixed by the dynamically conserved quantities (usually represented by *coherent states*, i.e., narrowly peaked Gaussians in both position and momentum) (Zurek 1993). Zurek, Habib and Paz (1993) have shown in some models that the $|\psi_i\rangle$ in (5) correspond to the states that are maximally stable (and invariant) under decoherence in the sense that all other states of the system approach the diagonal form (7). Moreover, the coherent states minimize the production of (von Neumann and linear) entropy (so that $\rho_s(t)$ becomes maximally mixed when diagonalized by coherent states). In this sense decohering systems are said to follow quasi-classical trajectories and exhibit quasi-classical behavior.

As we sketched above the states $|E_i(t)\rangle$ of the environment *relative* to the $|\psi_i\rangle$ in (5) *separate and don't reinterfere* again. This is because the $|E_i(t)\rangle$ remain over extremely long times (approximately) orthogonal during the evolution of the quantum state. This means that the correlations between the $|\psi_i\rangle$ and the $|E_i(t)\rangle$ are in fact stable over time under the Schrödinger evolution. In this sense one can say that the $|E_i(t)\rangle$ at later times are *records* of the $|\psi_i\rangle$ that occurred at earlier times.

1. Also, in the standard models the decoherence times of the system are much shorter than the dynamical times even for very weakly dissipative systems. The relaxation times are typically extremely long, in some models of the order 10^{40} sec.

Here is one way to read the MWI.² Branches of the universal state $|\Psi(t)\rangle$ of the form (5) exist essentially at all times comparable with the typical decoherence times. These branches can be characterized as follows. (A) They have a product form $|\psi_i\rangle \otimes |E_i(t)\rangle$ which is essentially invariant under the time evolution of $|\Psi\rangle$, and in particular, the branches don't reinterfere over sufficiently long times. (B) The $|\psi_i\rangle$ correspond to approximate eigenstates of the classically conserved quantities and typically they follow quasi-classical trajectories. (C) The quantum mechanical measure (given by the amplitude squared $|\mu_i(t)|^2$) defined over these branches exhibits formal features of probability. This last point is crucial since in the MWI the measure is supposed to induce in some sense the *frequencies* along the branches. Suppose now, following Everett (1957), that all *branches* of the universal $|\Psi(t)\rangle$ (relative to any choice of basis) are equally real, and let us associate any such branch structure with a set of *worlds*.³ It follows that there are sets of worlds associated with branches defined by decoherence, and so these worlds may be taken to correspond to our experience.

There is a direct correspondence between branches in the MWI and sets of decoherent histories in the histories approach to quantum mechanics (Griffiths (1984), Gell-Mann and Hartle (1993)). In this approach the probabilities for individual histories are given by

$$|C_\alpha | \Psi \rangle|^2, \quad (8)$$

where C_α is a quantum history⁴, a string of projections at a sequence of times $t_1 < t_2 < \dots < t_n$:

$$C_\alpha = P_{\alpha_n}^n(t_n) \dots P_{\alpha_1}^1(t_1), \quad (9)$$

with mutually exclusive and exhaustive projection operators at each time $P_{\alpha_i}^i(t_i)$. In the Heisenberg picture $|\Psi\rangle$ is fixed and the set of projectors $P_{\alpha_i}(t)$ evolves in time in accordance with

$$P_\alpha(t) = e^{iHt} P_\alpha e^{-iHt}. \quad (10)$$

The probabilities in (8) correspond to a sequential application of the Born rule in standard quantum mechanics. They are additive if any two histories C_α and C_β in a given set satisfy a *decoherence* condition: that is

2. This reading is based on Bacciagaluppi and Hemmo 1995. It is close to the versions by Zeh (1973), Saunders (1995), Vaidman (2002).

3. Perhaps a set of worlds should be associated not with an exact branch structure, but rather with a *bundle* of branches all of which elements are pairwise close to each other in some measure theoretic sense (see Bacciagaluppi and Hemmo 1995).

4. We assume, for simplicity, throughout that the initial state of the universe ρ_{in} is pure $\rho_{in} = |\Psi\rangle\langle\Psi|$.

$$\langle \Psi | C_\alpha^\dagger C_\beta | \Psi \rangle \approx 0, \quad \alpha \neq \beta, \quad (11)$$

which essentially means that the histories in the set don't interfere. This (or other related) decoherence condition(s) is taken to be necessary and sufficient for assigning the probabilities (8) to the histories C_α in a given set.⁵

A theorem proved by Gell-Mann and Hartle (1993) and Halliwell (1995) says that a set of histories satisfies the decoherence condition (11) *if and only if* the histories in the set are *recorded* in the states of some subsystem of the universe. Histories are defined to be recorded, roughly, if at any time $t > t_n$ after the last projection in the set there are sequences of exhaustive and alternative projections that are in perfect correlations with the histories in the set. In the context of the MWI it is important to note that this theorem doesn't uniquely single out branches that match our experience: there are branchings associated with decoherent sets of histories in which the projections correspond to superpositions of quasi-classical trajectories. But the converse is invariably true: pointer basis histories which are recorded in the relative states of the environment satisfy the decoherence condition (11).⁶

As is well known the above sketch of the MWI is not complete, because of the so-called probability and preferred basis problems (see Vaidman 2002). But I shall assume now that it is completeable, and focus on the question of the direction of time.

3. The Direction of Time. The branches associated with quasi classical behavior in the sense described above don't reinterfere, because the $|E_i(t)\rangle$ don't due to decoherence. In the version of the MWI sketched above this condition is taken as a characteristic feature of the branches that are associated with our worlds. This has the consequence of an effective collapse along the quasi classical branches. That is, the branches after a split evolve independently of each other (as it were, in 'parallel'). As a result, a *time directed* collapse seems to have occurred at each split (from the point of view of a branch). This means that the branching associated with our worlds has *effectively* a tree-like form in which on the backward (past) direction of time a branch has a unique continuation, whereas on the forward (future) direction it splits. In other words, the histories corresponding to our worlds seem to follow a tree-like divergence pattern. Note that the tree picture is a bit misleading: on the one hand in the MWI the evolution of the total wave function is time reversible, and in this sense we can retrodict a unique past (see below). On the other given

5. See Dowker and Kent 1996 for a critical evaluation of the histories approach.

6. A direct proof is given by Zurek (1993); see also Hemmo 1996, ch. 5.

the present data *in a world* we cannot retrodict a *unique* past. Hartle (1997) shows that, in general, retrodictions of the past in the latter sense conditional on present data are nonunique for almost any decoherent set of histories, even though they are assigned probability one.

On this picture the process of decoherence itself exhibits time asymmetry. This is because the interaction with the environment increases the degree of mixing of the (reduced) state of the system in the *forward* (and not in the backward) direction of time. Also, the decoherence condition (11) displays an asymmetry in time. Take the set of histories C_α (call it the *forward* set), and consider the *backward* set, i.e., the set of histories that unfold, as it were, backwards in time from t_n to t_1 . Then for a given ρ_{in} the decoherence conditions of the forward and the backward sets are in general *not* equal, and in particular the histories in the two sets will not decohere together (Hartle 1997; Bacciagaluppi 2001). Thus the branches corresponding to our histories can satisfy either the forward decoherence condition or the backward one, but not both. This time asymmetry is reflected in the probabilities for histories (8) (and in the frequencies they should match along a history), which are explicitly time asymmetric, because they invariably depend on an *initial* or past state $|\Psi\rangle$, and not on a final or future state.

The above time asymmetries may be taken to suggest that in the MWI the direction of time as fixed by decoherence is fundamental (see Zeh 1992, ch. 4 for an extensive discussion). This intuition can be justified as follows. Along the branches associated with our worlds we have an effective collapse onto quasi classical states. This collapse is manifestly time directed. The tree-like form of the branches in the case of decoherent sets of histories distinguishes between the future and the past directions of time. Furthermore, the time asymmetry of the decoherence condition itself suggests that the direction of time we experience (along our histories) is fixed by either the forward condition of decoherence or the backward one (Bacciagaluppi 2001).

However, in the MWI the dynamical equations of motion of the universal state are completely time symmetric. In the MWI the collapse of the state has only an *effective* status, no matter how we further choose to interpret it.⁷ In fact, the appearance of a collapse (relative to a branch along a given set of branches) is a straightforward result of the decoherence condition. But, in general, it is the initial state of the universe ρ_{in} and the dynamical conditions that completely determine whether or not a given set of histories is decoherent for any given sequence of times. In particular, the dynamics and the initial conditions fix completely whether any future (or past) extensions of a given set of histories remain decoherent (i.e., whether

7. In a relativistic setting, for example, the collapse can be hyperplane-dependent, or it can be stipulated to occur along future light cones (see Bacciagaluppi 2001).

the histories don't reinterfere in the future or past). As long as the future extensions of our histories belong to a decoherent set, the frequencies we shall observe will exhibit the above time asymmetries. But this, in turn, is fully determined by the initial conditions and the dynamics. The theory leaves, as it were, no room for a fundamental direction of time.

In the case of decoherence through interactions with the environment, the standard models usually make the following assumptions: (I) The interaction between the system and environment takes the form of (3). (II) The initial total state is factorizable (i.e., a state of *minimal* entanglement; see equation (4)). (III) The phases of the environment states $|E_i(t)\rangle$ are uniformly distributed. These three assumptions imply that the $|E_i(t)\rangle$ have low probability to reinterfere over sufficiently long times (so that over time $\rho_s(t)$ keeps its diagonal form (7)). That is, in the MWI the direction of the evolution we perceive along our histories, namely that the evolution is from pure to mixed states and not the other way around, is not determined by the form of the dynamics (I) alone, but also by the initial conditions (II) and (III). Therefore, the direction of time fixed by decoherence through interactions with the environment is not purely dynamical, and in this sense it is not fundamental in the MWI. Moreover, (II) is a highly implausible assumption, if there are enough particles in the environment: that is, the set of factorizable states in this case has measure zero in the total Hilbert space of system and environment (but perhaps it is not necessary for decoherence; see Arntzenius 1998).⁸ Also, the statistical distribution in (III) (although natural) is not unique, and in any case it is not implied by the quantum dynamics, nor by the quantum probabilities.

In the histories approach the time *symmetry* of the dynamics is often stated by adding a final condition ρ_{fin} to the probabilities (8) (Aharonov et al. 1964), and to the decoherence functional (11) (Gell-Mann and Hartle 1993). And the time asymmetry of the transition probabilities (and the observed frequencies along our histories) is, again, traced back to some special initial condition $\rho_{in}=|\Psi\rangle\langle\Psi|$ that is consistent with present data. From this perspective the above time asymmetries seem to be a consequence of an asymmetry between initial and final conditions. But, again, in the MWI this does not imply that the direction of time is fundamental.⁹

4. The Thermodynamic Arrow. A detailed quantum mechanical analysis of the connection between decoherence theory and thermodynamic behavior of a classical chaotic system is given by Zurek and Paz (1994) (and also by

8. This is the Haar measure defined on finite-dimensional Hilbert spaces, which is invariant under the unitary transformations (see Arntzenius 1998).

9. A more fundamental analysis of time asymmetry requires a background (quantum) theory of space and time; see Halliwell, Perez-Mercader, and Zurek 1992 for mainstream papers on this topic.

Zurek, Habib and Paz (1993)). I don't have space here to display their results in detail. In their models they consider a chaotic system that is subjected to a decoherence interaction with its environment, and show the following. (I) The quasi-classical states of the system picked out by the decoherence interaction (see Section 2) are the most stable states under which the production of the von Neumann entropy goes down to a minimum. (II) After extremely short times (comparable to the decoherence times; but see below) during the decoherence interaction the system follows quasi-classical trajectories (this should be understood in the context of a proper interpretation of quantum mechanics only). (III) The quantum mechanical von Neumann entropy $-k\text{Tr}\rho\ln\rho$ typically increases as a monotonic function of time, and moreover it is naturally interpreted in terms of increase in phase space volume. (IV) The rate of increase of the von Neumann entropy is fixed essentially by the rate of divergence of the chaotic system (e.g., by the Lyapunov exponents), so that the classical predictions are recovered. (V) The above results don't hold for closed (isolated) systems (for more details, see Zurek and Paz 1994 and references therein). This last point means that classical mechanics would be directly *refuted* if only we could perfectly isolate a chaotic system from its environment (e.g., if the above models are right, the entropy of the system would be constant throughout its evolution even if the system were to start in a non equilibrium state).

Let us now suppose that these models of decoherence are correct, and that they can be generalized to all realistic cases of thermodynamic systems, such as gases spreading out in a container, or gases embedded in clouds of other gases with much lighter molecules (where the container and the lighter gases play the role of decohering environments), etc. We want to consider the implications of these models in the MWI regarding the question of the direction of time. In the MWI the very definition of the branches corresponding to our histories stipulates that they belong to a decoherent set of histories, due to, interactions of macroscopic systems with the environment. In Section 2 we saw that in the MWI the dynamics of a macroscopic system along our histories can be seen as corresponding to a dense sequence of (effective) collapses separated by decoherence times. At intermediate times between collapses, the system seems to evolve (on each branch) from an effectively pure state to a quantum mechanical mixed state (after a split) approaching a diagonal form as in (7). In the pointer basis expansion, this mixture corresponds to outgoing branches on which the system is described by quasi classical states (e.g., coherent states, or more generally, eigenstates of conserved quantities).¹⁰

10. This should not hold in models of decoherence with *no* fixed pointer basis, e.g., in extremely light gases, but also in this case decoherence presumably produces the classical correlation functions. I thank professor Dieter Zeh for pointing this out to me.

Actually we can say more, given the above results of Zurek and Paz (1994). During the process of decoherence the (quasi) classical form of the reduced state of the system $\rho_s(t)$ seems to play the role of a quantum mechanical equilibrium state in two respects: (i) all other states of the system evolve under decoherence towards $\rho_s(t)$; and (ii) $\rho_s(t)$ represents the most stable probability distribution over the quantum states of the system. And so in the MWI $\rho_s(t)$ may be taken to replace the standard probability measure of classical statistical mechanics.¹¹ In this sense the probabilities of classical statistical mechanics may be entirely reduced to the quantum probabilities.¹² In fact, if the above models are correct, it is plausible that the splitting of the branches reproduces the standard probability measure of classical statistical mechanics. Thus we may have a unified dynamical origin of the probabilities in physics (compare this to Albert's GRW based approach to the foundations of classical statistical mechanics (2000, ch. 7); see the next section).

Assuming that these results in decoherence theory are generic, one may want to argue that in the MWI the *time asymmetry* of thermodynamic evolutions is built into the dynamical equations of motion, since the thermodynamic regularities are a consequence of the dynamical evolution of the wave function in decoherence situations. However, this is wrong. The argument is akin to the usual Loschmidt objection from time reversibility (see also the end of Section 3). Recall that the Schrödinger equation (and its relativistic analogs) are time-reversal invariant. This implies that the evolution of the (total) quantum state of system and environment in decoherence situations is in principle time reversible. Moreover, the process of decoherence itself is a result of the time symmetric dynamics only on the statistical hypothesis of a uniform probability distribution over the phases of the environment states. And so, as a matter of principle, there must be entropy *decreasing* trajectories along which the quantum state may evolve in the future direction of time.

This means that in the MWI whether or not entropy will actually decrease in the future of our branches depends on initial conditions. Entropy will invariably increase along branches corresponding to the classical variables provided we assume that these branches will not reinterfere in the future. If reinterference will occur, the evolution will result (with certainty) for some initial states in entropy decrease. In the MWI whether or not this will occur depends entirely on initial conditions.

11. I assume here that in the MWI $\rho_s(t)$ might be taken to represent a genuine probability distribution over the branches; this is under dispute.

12. Compare a similar argument by Wallace (2001) and Hemmo and Shenker (2001, 2003a). Classical approaches to equilibrium states don't seem to be applicable in quantum mechanics (see Wallace 2001).

In fact, there is no sense which doesn't bear on statistical assumptions about the distribution of initial states, in which reinterference of our branches is unlikely at any finite time. No physical law in the MWI rules out the possibility of a complex demon making an interference experiment with our branches ten minutes from now. Such experiments may well violate the second law of thermodynamics. In this sense it is not fundamental, nor does it entail in the MWI that time has a direction.

5. Conclusion. An alternative approach in which a fundamental direction of time, in particular the thermodynamic arrow, is fixed by the dynamical equations of motion in quantum mechanics has been proposed by Albert (2000, ch. 7). If the underlying quantum mechanical theory is the collapse theory by GRW (see GRW 1986; Bell 1987), then the dynamical equations of motion of isolated systems are time asymmetric (since the GRW equations of motion are non-invariant under time reversal). A history, say of a thermodynamic system (closed or open) unfolds, according to the GRW theory, in a time-directed fashion fixed by the direction of the dynamics. In addition, the dynamics results in a random walk on a set of alternatives with the probabilities given by the quantum mechanical algorithm. For a given quantum state before a collapse, the GRW dynamics gives a set of transition probabilities over the possible states of the system immediately after the collapse. Albert (2000, 155–156) argues that given the GRW parameters for a collapse, the transition probabilities in this theory plausibly entail the standard probability measure of classical statistical mechanics.¹³ If true, this means that thermodynamic evolutions are, with high probability, time *irreversible*, and that entropy decreasing trajectories are both highly improbable and unstable. In this sense, Albert's approach may underwrite by pure dynamical laws a fundamental direction for time, the thermodynamic direction included (see also Arntzenius 1997; Callender 1997). Moreover, it would also entail that the classical ignorance-type probabilities are reduced to the quantum probabilities (see below).

Since the GRW dynamics is time asymmetric, Loschmidt-like objections (relying on time reversibility) are not applicable to it.¹⁴ Likewise in the GRW theory quantum mechanical reinterference experiments of the kind considered above are not applicable, because all but one of the branches of the quantum state really vanish due to the GRW collapses. However, because of the time asymmetry of the dynamics, the GRW theory can produce no *retrodictions* at all. The retrodiction that entropy

13. This is plausible, but not yet proved in the GRW theory.

14. For how Loschmidt-like reversals (the *spin echo* experiments) are explained in this theory, see Albert 2000, ch. 7; Hemmo and Shenker 2003b.

decreases in the future-to-past direction of time can be produced only by introducing a *past hypothesis* according to which the *initial* macrostate of the universe was a state of low entropy (see Albert 2000, ch. 7). But due to the *stochastic* nature of the GRW collapses, the past hypothesis need only apply to the initial *macro* and not microstate of the universe. In fact, if the GRW theory is true of our world, it is highly plausible that no statistical assumptions at all are required about the distribution of *microstates* in order to derive the thermodynamic regularities.

In the MWI a past hypothesis of low entropy initial states is also required, though here it is to block the usual Loschmidt objection from time reversibility. However, in this context decoherence seems to yield an interesting result. The initial *micro*-conditions (see (II) in Section 3) required in the decoherence models imply that the initial total quantum state is of low von Neumann entropy. In the model of decoherence described in Section 2 the condition of low entanglement of the initial (product) state of system and environment means that the initial state of the system is already a state of minimal von Neumann entropy (which is equal to zero, if the initial state of the universe is pure).¹⁵ And so no past hypothesis about the initial macrostate of the universe, and in particular no past hypothesis about the initial microstate of the thermodynamic system, is required over and above the initial conditions required for decoherence. In sum: no specific reference to any *thermodynamic* feature of the initial micro—(or macro)—state of the universe need be made, although assumptions about micro initial conditions are required.

My conclusion about the connection between the quantum probabilities and the direction of time is this. In Albert's GRW-based approach there is a time-directed collapse which is built into the dynamics of the quantum wave function. This dynamics, arguably, yields the thermodynamic regularities. And so, in this theory the observed direction of thermodynamic processes is fixed by the direction of time as defined by the dynamics. By the laws of motion of the GRW theory, therefore, thermodynamic processes are fundamentally irreversible. And since the GRW collapse is *stochastic*, the thermodynamic arrow is independent of initial *micro*-conditions.¹⁶

In the MWI, by contrast, there is only an apparent connection between the quantum probabilities and time direction. The thermodynamic arrow may be recovered (effectively) along quasi-classical histories on the basis of the diffusion of correlations into the environment. But as a matter of

15. I thank Guido Bacciagaluppi for raising this point, and Itamar Pitowsky for discussions. See Hemmo and Shenker 2003b.

16. Note that stochastic dynamics is compatible with time reversal invariance, if, for example, the forward and the backward transition probabilities turn out to be equal (see Callender 2002). But this is not the case in the GRW theory.

principle the process of decoherence is perfectly time reversible. In particular, as we saw above, the recovery of thermodynamic regularities in the MWI doesn't depend in any way on whether or not the transitions along a history (when the wave function splits) are stochastic. In fact, even if they were truly stochastic, say denoting a chance process,¹⁷ they will still have no impact on the question of time reversibility. A similar analysis applies to Bohm's theory and to modal theories (see Dieks and Vermaas 1998). It turns out that in all those theories the extra dynamics of the hidden variables are time reversal invariant. I conjecture that it *must* be so.¹⁸

If this is true, it means that in no-collapse quantum mechanical theories any stochastic dynamics over and above the quantum wave function cannot determine a fundamental direction of time. In quantum mechanics without collapse all mechanical and thermodynamical processes are time reversible, just because the dynamical evolution of the wave function is. The quantum probabilities may have an effect in determining a direction of time only in so far as they are reflected in the dynamics of the *wave function* (as in the GRW theory; see Albert 2000, ch. 7). But, in the MWI this is not the case: the transition probabilities along our histories have no impact on the dynamics of the (total) wave function (no matter how they may be interpreted). Hence, there can be no fundamental direction of time in the MWI.

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17. The question is open; see fn. 12.

18. Assuming that hidden variables theories are empirically equivalent to quantum mechanics, the flow of the probabilities in any such theory must be controlled by the time reversal invariant dynamics of the wave function; and nothing else. This should hold also in the MWI and its many minds variants.

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