Does Indeterminism Give Rise to an Intrinsic Time Arrow? *

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June 17, 2018

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Abstract

In any physical theory that admits true indeterminism, the thermodynamic arrow of time can arise regardless of the system’s initial conditions. Hence on such theories time’s arrow emerges out of the basic physical interactions. The example of the GRW theory is studied in detail.

1 Introduction

Our experience suggests that the universe’s evolution is invariably time-asymmetric, that is, that events evolve one after another from past to future.

\textsuperscript{*}Submitted to Studies in Hist. and Phil. of Mod. Phys.

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If this intuition is correct, then time’s apparent arrow should be intrinsic to the fundamental dynamical laws describing our universe. However, this intuitive impression is contradicted by current physical theories, according to which the fundamental dynamical laws of the universe are without exception *time symmetric*, i.e., invariant under time reversal.

In view of this time symmetry of physical laws, most accounts in the foundations of physics appeal to *statistical* assumptions concerning certain special boundary conditions in order to account for the apparent arrow of time. There are, however, a few attempts (see e.g. Penrose [15]) to account for this arrow of time by making an appeal to a new physics which would explicitly include within the dynamical equations of motion a time-asymmetric component.

Another unresolved question in the foundations of physics is whether *determinism* holds at the microscopic level. Here opinions are more evenly divided. In quantum mechanics, for instance, some interpretations postulate dynamical equations of motion that are completely deterministic (e.g. Bohm’s pilot-wave [17] and Everett’s many worlds interpretation [18]), whereas other interpretations, following early ideas of von Neumann [1] and Dirac [2], attempt to rewrite the fundamental quantum mechanical laws by proposing *indeterministic* equations of motion (e.g. the collapse theory of Ghirardi, Rimini, and Weber (GRW) [22] and Penrose’s [4] hypothesis of gravitational collapse). Genuine stochastic dynamics has also been invoked in other fields of physics, e.g. black-hole thermodynamics (Hawking and Penrose [20]) and general relativity (Earman [19]).

These two questions, that is, the questions of whether the fundamental dynamical laws contain an (as yet unknown) intrinsic time arrow, and whether or not they are genuinely deterministic, went on nearly oblivious to one another. In this paper we would like to study their bearings on one another in detail.

The structure of this paper is as follows. In section 2 we discuss three types of uncertainty and their physical manifestations. In section 3 we show the fundamental affinity between indeterminism and entropy. In section 4 we briefly review the GRW theory, then in section 5 we review Albert’s method.
of deriving the thermodynamic arrow from quantum collapse. Finally, we
discuss the broader connection between the stochastic dynamics and the
arrow of time.

2 Three Uncertainties and their Physical Manifestations

Let us begin with some theoretical considerations of uncertainty, reversibility,
and determinism. We will use the term “uncertainty” to denote the strong,
ontological sense of the term. In other words, we do not refer to the observer’s
mere ignorance but to the real absence of any strict cause-effect relations
between two event. We make use of the notion of causation here in an
intuitive way without appealing to any specific theory of causation. An
operational definition for such uncertainty is as follows:

If event $A$ is uncertain and event $B$ is its cause (effect), then, repeating
the process in the forward (backward) time direction will not always reproduce
$A$ from $B$.

Such an uncertainty can take one out of three forms, which we shall denote
by “$V$,” “$Λ$,” and “$X$,” according to these letters’ shapes (as in Fig. 1).
Strict determinism will be represented by $I$, since it has a linear topology:
each initial event $C$ constitutes a cause for only one effect $E$. Indeterministic
theories can have one of the following topologies: “$V$ uncertainty” arises when
a certain cause $C$ can give rise to more than one possible effect: $E_1$, $E_2$, ...
“$Λ$ uncertainty” is the inverse case where a system can start at any one out
of some initial states, $C_1$, $C_2$, ..., but always reaches one final state $E$.
“$X$ uncertainty” is a combination of the former two: an event can have several
initial causes, $C_1$, $C_2$, ..., as well as several effects, $E_1$, $E_2$, ...

Note the following:

- Only $Λ$ and $V$ topologies are asymmetric under time reversal, and as
such have a “built-in” microscopic time arrow. This microscopic time
arrow may, or may not, manifest itself at the macro level, for instance in the form of a thermodynamic arrow (in accordance with the second law of thermodynamics). However, any further discussion on the arrow of time becomes superfluous, since its origin is apparent.

• **V** uncertainty is what we call “indeterminism”, since the present state of the system cannot help predicting its future state. However, such a topology is reversible since reversing the system from any of the effects $E_1$, $E_2$, ..., will always yield the initial cause $C$.

• **Λ** uncertainty, on the other hand, is deterministic in the forward time direction, but irreversible (in the sense just defined).

• All but **X** uncertainty are not accessible to empirical investigation. In **I** topology, for example, a system can be prepared in such a way as to either increase or decrease its entropy, depending only on the initial state. Hence, as Hawking [21] pointed out, we might be living in a universe that actually evolves from what we call “future” to our “past”, and we wouldn’t notice, as our perceptual mechanisms would be reversed accordingly. Similarly, since **V** and **Λ** uncertainties are mirror images of one another, we could be living in a world having one topology which nevertheless evolves from “past” to “future” (in some absolute sense), or *vice versa*. Neither experience nor experiment can distinguish between these possibilities.
• Hence, only $X$ is a testable hypothesis, which we shall study in what follows.

Returning to physics, it is quantum mechanics where one would look for examples for such uncertainties. We would like to state that uncertainty in physics always comes in the $X$ topology. For that purpose, consider the experimental setup in Fig. 2a. Here an electron source emits electrons in an $x$-spin up ($x^+$) state. These electrons pass through a Stern-Gerlach (S.G.) magnet that splits their path according to their $z$-spin. Then the electrons can hit, with a 50-50 probability, one of the two detectors: $A$ for $z^+$, or $B$ for $z^-$.

In a world of indeterministic dynamics (such as von Neumann’s “collapse”, or GRW\(^1\)) one would intuitively classify its topology to be $V$, such as in Fig. 1b: here one initial state $C$ (the electron at spin $x^+$), gave rise to one out of two effects: $E_1$ (the electron hitting $A$ with spin $z^+$), and $E_2$ (the electron hitting $B$ with spin $z^-$). However, $V$ topology must be strictly reversible, and this is not the case here: reversing the operation of the detector that has clicked will cause the electron to reach the source in either a $z^+$ or a $z^-$ state, in contrast to state $C$ where a spin $x^+$ electron was emitted.

\(^1\)What we say in what follows applies only to the discrete model of the GRW theory. In the continuous model the dynamics turns out also to be time irreversible, but for different reasons related to the behavior of the tails of the collapsed wavefunction (see footnote \(^3\) for more details).
In order to resolve this inconsistency, let us look at Fig. 2b. Here the apparatus is extended to the past to explain how one could make an $x+$ spin source: one has actually used a generic electron source and passed the output beam through an X-S.G. Only the $x+$ part was allowed to continue the experiment. Now, reversing the experiment will, in 50% of the cases, return an $x+$ electron to the source $S$.

However, there is another possible past for the system. The electron could have been emitted in a $X-$ spin state from source $P$, and reach exactly the same probabilities for the final states $E_1$, and $E_2$. This additional possible past now completes the picture, since reversing from these final states might cause the electron to be deflected down at the $x$-S.G. and reach source $P$.

Now we can see that in an indeterministic theory the dynamics can be time reversed in the above sense provided there are two possible pasts - that is, an $X$ topology. Note, however, that the $X$ might not be completely time-symmetric, that is $C_1$, and $C_2$ need not be equal to $E_1$, and $E_2$.

Note further that in the case of collapse interpretations of quantum mechanics such as the GRW theory (and von Neumann’s theory) the $X$ shape situation means that the statistical results of measurements that may be carried out on a system at a given time (that is, of measurements of commuting observables) are in principle insufficient in order to built up, by retrodiction, the initial wavefunction of the system. Of course, in quantum mechanics without collapse it is also true that the actual statistics of results is insufficient to retrodict with certainty the wavefunction, but in such theories it is also true that the overall state of the world after a measurement is described by the uncollapsed wavefunction which obeys a completely deterministic and time reversible dynamics (i.e. the Schrödinger equation).

Next we shall consider the bearing of these conclusions on the origins of the thermodynamic arrow of time.

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2One can, however, built up the wavefunction from the (counterfactual) statistical results of all possible measurements which would include non-commuting measurements.
3 When Determinism Fails

In most physical discussions, “irreversibility” is used in the technical, hence relative sense. Processes like milk being spilt or a match being burnt are irreversible only in the practical sense because, in principle, a sufficiently advanced technology can reverse them. Indeed some processes considered irreversible by past standards are becoming reversible today.

Notice, however, that when referring to “sufficiently advanced technology,” one has in mind a kind of nanotechnology that can reverse, precisely and simultaneously, the motions of a myriad of molecules, so as to get spilt milk gathered anew in the jar and a match re-assembled from charcoal, smoke, and thermal photons. Now, this sense of reversibility rests on a highly non-trivial assumption that must no more be left tacit. To say that a process can be microscopically reversed, one must profess absolute determinism. It is only strict determinism that guarantees that, once the momenta of all molecules of a system are reversed, the system will return to its initial state.

Fig. 3 gives a simple illustration for this principle. A set of Newtonian balls (hence, harboring an I topology) is simulated in the forward and backward time directions at absolute precision. In Fig. 4, an event of X indeterminism is inserted by a single random interference with the position of a single ball. It is common knowledge that, for a normal system whose entropy increases, a slight interference will make no difference for the overall entropy increase. The final macrostate affected by the interference will be indistinguishable from the final state that would ensue otherwise. In contrast, an entropy decreasing system is extremely sensitive to interference: It requires a very special microstate at any instant, and the slightest interference will ruin its entropy decrease. Hence, the system will fail to converge to the desired ordered state.

What makes this seemingly trivial observation crucial in the context of time’s arrow is this: Regardless of the system’s initial conditions, its entropy always increases following the random event. If these initial conditions are of the normal, entropy-increasing type, the random event would merely strengthen entropy increase. If, on the other hand, they are of the unique,
Figure 3a: A computer simulation of an entropy increasing process, with the initial and final states (right) and the entire process using a spacetime diagram (left). One billiard ball hits a group of ordered balls at rest, dispersing them all over the table. After repeated collisions between the balls, the energy and momentum of the first ball is nearly equally divided between the balls.

Figure 3b: The time-reversed process. All the momenta of the balls are reversed at t=350. Eventually, the initial ordered group is re-formed, as at t=0, ejecting back the first ball.
Figure 4a: The same simulation as in 3a, with a slight disturbance in the trajectory of one ball (marked by the small circle). Entropy increase seems to be indistinguishable from that of 3a.

Figure 4b: The same computer simulation as in 3b, with a similar disturbance. Here, the return to the ordered initial state fails.
entropy-decreasing type, the random event would most probably flip the system’s evolution back towards entropy increase. Hence, genuine indeterminism at the micro scale enforces a macroscopic time arrow that has nothing to do with initial condition. Rather, it seems to be intrinsic (see also Elitzur and Dolev [12, 13, 14]).

A similar conclusion has been reached by Albert [9, 10], who studied the indeterminism entailed by the GRW theory. We shall review the GRW interpretation in the following section, and Albert’s arguments afterwards.

4 The GRW theory

The GRW theory [22] is an interpretation of QM in which the von Neumann collapse is built into the dynamics of the wavefunction itself. There is no talk about measurement, observation, decoherence, or anything like that, and there is no need for thumb rules that somehow distinguish between the classical and the quantum levels, or system and its environment. According to GRW, any system whatsoever has a quantum state, and that state evolves under a single dynamical equation of motion. Quantum mechanics can be applied to any system whatsoever, including the universe as a whole. However, the theory explains, as a straightforward result of the dynamics, why systems consisting of a large number of particles (i.e. macroscopic systems) do not usually exhibit quantum interference (Schrödinger cats and measuring devices included). The theory in its most simple (and nonrelativistic) form goes as follows.\footnote{Here we follow Bell’s discrete model [3].}

Consider the quantum wavefunction of a composite system consisting of $N$ particles:

$$|\Psi(x_1...x_N, t)\rangle.$$  \hspace{1cm} (1)

The time evolution of the wavefunction usually but not always satisfies the linear and deterministic Schrödinger equation. From time to time the wavefunction collapses onto some localized Gaussian in position of the normalized
form:

\[ G(x_k) = Ke^{-(x-x_k)^2/\Delta} \]  

(2)

where \( x_k \) is randomly chosen from the arguments in (1) and the width \( \Delta \) of
the Gaussian is stipulated to be approximately \( \Delta = 10^{-5} \text{cm} \). This parameter
is taken as a new constant of nature. The GRW jumps are also stipulated to
occur only in position, and this means that on this theory, wavefunctions that
are approximate eigenstates of position are taken to be physically preferred.

Two additional questions with respect to the GRW collapses need to be settled: first, When do they occur? and second, Where? According to
GRW, the answers to both questions are a matter of probability. Concerning
the first, the probability \( \tau \) for a collapse for a single particle at any given
time is stipulated to be approximately \( \tau = 10^{-15} \) (again a new constant of
nature). Concerning the second question, the probability that the reduced
wavefunction will be centered around any spatial point \( x \) at time \( t \) is given
by the standard Born rule:

\[ |\langle \Psi(x_1...x_N, t | G(x_k) \rangle|^2 \], \]

(3)

where \( G(x, k) \) is the GRW Gaussian defined in (2).

This is essentially the whole theory. However, three brief comments are
in order:

(1) The choice of the new constants of nature, i.e. the frequency of the
collapses \( \tau \) (which is proportional to the number of particles) and the width
of the Gaussian \( \Delta \) ensure that the collapses will not result in violations of
either our experience on the macroscopic scale, or of the well confirmed pre-
dictions of standard quantum mechanics. Moreover, the stochastic dynamics
is designed in such a way that the solution to the measurement problem in
the quantum theory of measurement, obtains a straightforward result of the
quantum mechanics of composite systems. In other words, any interaction
which involves the spatial displacement of a large number of particles (say,
in the pointer, or in records imprinted on a paper) will, with overwhelming
probability, result in a collapse of the wavefunction onto one of the eigenstates
of the pointer’s position with the usual Born probabilities.

(2) It follows from the GRW prescription that the collapses of the wave-
function might induce violations of both momentum and energy conservation. The GRW collapses will sometimes give rise to increase in momentum, in which case electrons might jump out of their orbits in the atoms. Similarly, they might increase the energy of a given cloud of gas just enough to heat it up, whereas we know experimentally that such things do not occur. However, $\Delta$ is chosen here to be wide enough so that the violations of the conservation laws will be small enough so as to be unobserved. So (in principle) it seems as if in the GRW theory there is a trade off between getting the second law of thermodynamics right, by the price of making the first law approximate. Note that if the GRW collapses were to occur onto delta functions in position, the violations of the conservation laws would be observable.

(3) $\Delta$ is chosen to be narrow enough so that the GRW collapses map the wavefunctions onto states that are close (in Hilbert space norm) to eigenstates of position, so that the positions become only approximately definite. This means that the GRW hits do not set the systems onto definite position states, but rather onto superpositions of positions with nonzero tails. But the amplitudes of these tails are small enough, so that the superposition has no observable effects, and the particles behave as if they actually have definite positions. Moreover, it turns out that these tails play an important role in the attempts to write down a relativistic version of the GRW theory.

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4 This yields the so-called tails problem: see Albert [11]. Also, when and where the hits occur in measurement situations might drastically vary. For some measurements it turns out that the GRW collapses are unlikely to occur prior to the interaction with the observer: see Albert and Vaidman [8].

5 In the case of the continuous, relativistic, model of the GRW theory the time reversed evolution in standard quantum mechanics (with no collapse) and in the GRW theory coincide. That is, on this model the almost zero tail of the "down" wavepacket will grow as the wavefunction is evolved backwards in time, so that the reversed wavepackets will exhibit the standard Schrödinger re-interference. This is by contrast to the almost negligible effect of the tail of the wavefunction in the course of the forward time evolution. In this sense also the continuous model of the GRW theory is not time reversible, though for a different reason. Note that the time irreversibility of the GRW tails turns out to be crucial in the case of relativistic versions of the theory. See Pearle [6]. Given this behavior of the continuous model, it is interesting to consider whether or not it remains genuinely stochastic.
5 Albert’s Derivation of Entropy Increase from Quantum Collapse

According to Albert [9, 10], the GRW theory provides a good candidate for reducing thermodynamics to mechanics, because its basic dynamical laws are fundamentally and irreducibly indeterministic. Moreover, the genuine stochastic collapse in the GRW theory is supposed to occur at the microscopic level with a frequency that suffices to actually derive the second law from the GRW dynamics.

Albert argues that a fundamental thermodynamic arrow intrinsic to the dynamics can be derived only in the GRW theory and not in other interpretations of quantum mechanics, such as Bohm’s theory, modal interpretations and the many worlds interpretations, since the latter are all deterministic and time reversible theories (topology). Following Albert, we argue that a genuine indeterministic dynamics is a necessary (though not sufficient) condition for deriving a fundamental arrow of time, including the thermodynamic arrow. That is, such a derivation can be carried only in theories which employ genuine stochastic equations of motion. By an intrinsic arrow of time we mean that the arrow of time should be solely a consequence of the dynamical equations of motion of the theory, and in particular it should be independent of initial (or final) conditions.

Here is one way to see how Albert’s reduction of the thermodynamic laws to the GRW theory is carried out. Consider, for instance, the special case of the approach to equilibrium of thermodynamic systems. Take $N$ molecules of some gas that is spreading out in a container. In standard (Schrödinger) quantum mechanics the composite wavefunction of the gas will almost always correspond to a state in which (due to quantum mechanical interactions) the molecules will be entangled with each other (and with the container walls), and moreover they will generally not be located in some definite positions within the container.

However, because of the high value of $N$, the $N$-particles wavefunction in the GRW theory has an overwhelming probability for collapses at almost every instant of time. Moreover, according to the GRW prescription the
wavefunction is reduced after a collapse to a Gaussian that is localized around some spatial distribution of the gas molecules. This means in particular that the solutions of the GRW equations of motion for the times at which collapses occur are approximately product states in position, where the molecules have in fact definite positions.

Finally note that this behavior critically depends on two factors. First, the number of particles in the system needs to be large enough to ensure the high probability for a GRW collapse. Second, the time evolution needs to be such that the wavefunction evolves into a superposition of terms corresponding to spatial locations of the molecules which differ more than the width $\Delta$ of the GRW Gaussian. If these conditions hold, the GRW jumps will invariably change the wavefunction of the gas in a way that is enough to put each molecule of the gas onto an apparently well defined trajectory. In particular, this behavior of the wavefunction is completely independent of initial conditions.

Recall now how mainstream physics tackles Loschmidt’s paradox. According to Loschmidt, by the same statistical considerations that have lead Boltzmann to predict entropy growth in the future direction, entropy should grow in the past direction too, as statistics itself is indifferent to the time directions. Against this paradox physicists invoke the low entropy past postulate (see Price [16]). This hypothesis simply imposes by fiat the low-entropy state in the universe’s past, in accordance with everyday observation. However, in the case of completely deterministic and time reversible theories this hypothesis means that the thermodynamic laws are recovered only for very special initial conditions which are (moreover) highly improbable.

In the case of the GRW theory, on the other hand, Loschmidt paradox simply does not arise. That is, the dynamics by itself does not entail that low entropy states in the past are just as improbable as low entropy future states. In this case, in order to settle the question whether or not entropy increasing trajectories in the future direction are highly probable, one has to actually solve the equations of motion of the GRW theory for the time in question. And that, as repeatedly stressed by Albert, is a straightforward empirical question (though perhaps not a tractable one in practice) about the predictions of the theory.
That is, given the GRW jumps, the question of the thermodynamic arrow of time becomes a completely empirical question. What is clear is that in the GRW dynamics there is a built-in mechanism in the form of the quantum jumps that as a matter of principle can send the system onto an entropy increasing trajectory independently of initial conditions, in a way similar to our simulation on Section 3. And this is ensured by the fact that the GRW dynamics is truly stochastic (or indeterministic), and a-fortiori time irreversible.

6 The Arrow of Time

We conclude our paper by generalizing our argument (Elitzur and Dolev [12, 13, 14]): A real arrow of time, that is an arrow of time intrinsic to the dynamical equations of motion, exists only in theories with indeterministic dynamics. In this sense, we argue that indeterministic X topology dynamics, as in the GRW theory, is a necessary (though not always sufficient) condition for deriving the thermodynamic arrow of time.

As is well known the postulated dynamics in most theories of current physics is time reversible. This means that in principle such theories cannot account for the thermodynamic arrow of time (and for our experience of the arrow of time) as intrinsic to the dynamical equations of motion. As we briefly discussed in section 3, such theories can recover the second law of thermodynamics only by appealing to the low-entropy past hypothesis. This applies to both classical statistical mechanics and to no-collapse quantum mechanics (including decoherence theories). In such theories no arrow of

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6 There are some extreme cases in which, as of principle, the GRW theory might not deliver the second law. But due to decoherence effects these are probably unobservable, see Albert [3].

7 Quantum weak interaction with CP violations notwithstanding.

8 We assume here that our experience of the arrow of time supervenes on physical processes.

9 For how to recover the thermodynamic laws in no collapse quantum mechanics, see Hemmo and Shenker [4]. It turns out, however, that environmental decoherence is a sufficient condition for deriving the thermodynamic arrow as an effective law.
time is built into the dynamics (since they are time reversible), and therefore no *intrinsic* arrow of time can be obtained from the dynamics, no matter what empirical evidence we have for the thermodynamic arrow. This is not the case in stochastic theories such as the GRW theory.

Thus it is crucial to bear in mind that even if the second law of thermodynamics (and thus the thermodynamic arrow of time) can be derived in completely deterministic and time reversible theories, this would mean that the thermodynamic behavior is recovered only as an *effective* behavior that crucially depends on some specific initial conditions. In this sense such behavior will not be intrinsic to the dynamics of the theory. The microcanonical distribution postulated by the traditional approaches to this problem in classical statistical mechanics, for instance, ensures that the second law can be derived as an effective law. But the microcanonical distribution itself does not depend on the dynamics and so thermodynamically pathological trajectories are in principle possible depending solely on the initial conditions of the system. Moreover, such trajectories turn out to be improbable, that is, they are assigned low probability (whatever probability means in the classical approach) only on the low-entropy past hypothesis.

Note that a theory might be genuinely stochastic and yet not deliver the thermodynamic arrow. For to derive the latter the stochastic dynamics at the macroscopic level must also be time irreversible, and (moreover) in the case of quantum mechanics the stochastic jumps must result in approximate eigenstates of *position*. That is, a stochastic theory in which the jumps were to occur, say onto some eigenstates of momentum, will definitely not yield the thermodynamic arrow. Since the above additional conditions on the dynamics are independent of whether or not the dynamics is stochastic, it follows that indeterminism by itself, even if it contains a built in arrow of time, is not sufficient to derive the thermodynamic arrow. This is, in fact, why other collapse theories such as von Neumann’s standard formulation will not be workable for deriving the arrow of time in general

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10 There is a sense in which the ergodic approach in classical statistical mechanics tries to derive the microcanonical distribution from the ergodicity of the dynamics. But it is not clear whether this approach can be successful. See Sklar for an overview of the problem and of the ergodic approach, and for references.

11 In von Neumann’s theory the stochastic dynamics comes to play only in measurement
In the case of the GRW theory, the quantum jumps are not time reversible, and that very fact allows to define, what might be called a *quantum mechanical arrow of time*. As we see from the above example, however, this arrow is completely independent of the thermodynamic arrow. But in the case of the GRW theory we saw that the dynamics alone can yields *also* the thermodynamic arrow of time. In this sense, in the GRW theory the thermodynamic arrow correlates with the quantum mechanical arrow of time. Moreover, if, as a matter of empirical fact, the GRW equations of motion will turn out to yield, with high probability, entropy increasing trajectories, then one could say that on this theory the thermodynamic arrow is *derived* from the quantum mechanical arrow. That is, what we have here is a proof that in the GRW theory the thermodynamic arrow can be built from the specific form of the GRW jumps.

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situations, and so the derivation will only hold for these situations. This means that on a such a theory there will be no *universal* thermodynamic arrow, since no measurements are carried out on the universe as a whole.
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