

The arrow of time, the nature of spacetime, and quantum measurement

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Abstract

This paper extends the work of a previous paper [arXiv:1108.5261v3] on top-down causation and quantum physics, to consider the origin of the arrow of time. It proposes that a ‘past condition’ cascades down from cosmological to micro scales, being realised in many microstructures and setting the arrow of time at the quantum level by top-down causation. This physics arrow of time then propagates up, through underlying emergence of higher level structures, to geology, astronomy, engineering, and biology. The appropriate space-time picture to view all this is an emergent block universe (‘EBU’), that recognizes the way the present is different from both the past and the future. This essential difference is the ultimate reason the arrow of time has to be the way it is. A bonus of this view, entailing the ongoing extension of spacetime as time flows on, is that closed timelike lines are naturally prevented (spacetime singularities will block them off). A conclusion of this view is that the process of state vector reduction is central to the flow of time, and is not restricted to laboratory settings or any formal process of observation.

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1 Quantum theory and the arrow of time

The arrow of time problem is one of the major foundational problems in physics [99, 34, 18, 48, 76, 105, 12], because the one-way flow of time embodied in the second law of thermodynamics emerges from time-symmetric microphysics. This paper builds on a previous paper [29], where the emergence of higher level structures and their top-down influence on lower level structures was considered to be a key factor in looking at the quantum measurement problem and the nature of the classical quantum cut. This paper will propose the same is true of the arrow of time.

The paper is structured as follows: Section 2 sets up the basic ideas underlying the rest of the paper: the basics of quantum theory, and the ideas of bottom up and top down causation in the hierarchy of complexity, and makes a main proposal as to how quantum theory underlies complex systems (Section 2.4.2). Section 3 discusses the arrow of time problem and various proposals that have been made to solve it, focussing on the Past Hypothesis in Section 3.3. Section 4 looks at the cosmological context and the various epochs relevant to discussing the issue of the flow of time, and how the basic cosmological arrow of time is set up. Section 5 proposes that the cosmological arrow of time cascades

down to lower levels in the hierarchy, each level in turn communicating the arrow to the next lower level. Section 6 discusses how the arrow of time then flows up the hierarchy as emergent structures form out of lower level elements, indeed being taken for granted in this context. Section 7 considers how the natural spacetime view to accommodate the experienced ongoing flow of time is an Emergent Block Universe that grows with time, and where the past, present and future are represented as having a quite different ontological character from each other. This provides the ultimate rationale for the arrow of time (Section 7.2) and resolves potential problems arising from the possibility of closed timelike lines (Section 7.3). Thus the overall picture that emerges is one of the arrow of time in physical systems being determined in a top-down manner, starting off from a special initial condition at the cosmological scale where the cosmological arrow time sets the basic direction of causation, but then emerging in complex systems through bottom up causation (Section 8). The relation to state vector reduction is crucial; obviously the details of that relation are still to be resolved (Section 8.1).

2 Foundations

To set the scene, this section summarizes some foundational issues discussed in more depth in [29]. It considers basics of quantum dynamics (Section 2.1), the hierarchy of structure (Section 2.2), and interlevel relations in that structure (Section 2.3). It then puts the main viewpoint underlying this and the companion paper (Section 2.4), emphasizing the interaction between bottom-up and top-down causation as a key feature of physics,

2.1 Quantum dynamics

The basic postulate of quantum mechanics [67, 79, 57, 46] is generically, the state vector $|\psi\rangle$ can be written as a linear combination of unit orthogonal basis vectors

$$|\psi_1\rangle = \sum_n c_n |u_n(x)\rangle, \quad (1)$$

where u_n is an eigenstate of some observable \hat{A} ([57]:5-7). The evolution of the system can be completely described by a unitary operator $\hat{U}(t_2, t_1)$, and so evolves as

$$|\psi_2\rangle = \hat{U}(t_2, t_1) |\psi_1\rangle \quad (2)$$

Here $\hat{U}(t_2, t_1)$ is the standard evolution operator, determined by the evolution equation

$$i\hbar \frac{d}{dt} |\psi_t\rangle = \hat{H} |\psi_t\rangle. \quad (3)$$

When the Hamiltonian \hat{H} is time independent, \hat{U} has the form ([57]:102-103)

$$\hat{U}(t_2, t_1) = e^{-\frac{i}{\hbar} \hat{H}(t_2-t_1)}. \quad (4)$$

Immediately after a measurement is made at a time $t = t^*$, however, the relevant part of the wavefunction is found to be in one of the eigenstates:

$$|\psi_2\rangle = c_N |u_N(x)\rangle \quad (5)$$

for some specific index N . The data for $t < t^*$ do not determine either N or c_N ; they only determine a probability for each possible outcome (5) through the fundamental equation

$$p_N = c_N^2 = \langle e_N | \psi_1 \rangle^2. \quad (6)$$

One can think of this as due to the probabilistic time-irreversible reduction of the wave function

$$\begin{array}{ccc} |\psi_1\rangle = \sum_n c_n |u_n(x)\rangle & \longrightarrow & |\psi_2\rangle = c_N u_N(x) \\ \text{Indeterminate} & \text{Transition} & \text{Determinate} \end{array}$$

This is the event where the uncertainties of quantum theory become manifest (up to this time the evolution is determinate and time reversible). It will not be a unitary transformation (2) unless the initial state was already an eigenstate of \hat{A} . More generally, one has projection into a subspace of eigenvectors ([57]:136; [102]:10-12) or a transformation of density matrices ([57]:137), or any other of a large set of possibilities ([102]:8-42), but the essential feature of non-unitary evolution remains the core of the process.

2.2 The context: the hierarchy of the structure

The context in which this all occurs is the hierarchy of structure and causation. Table 1 gives a simplified representation of this hierarchy of levels of reality as characterized by corresponding academic subjects, with the natural sciences on the left and the life sciences [11] on the right. On both sides, each lower level underlies what happens at each higher level in terms of structure and causation.

Level 10:	Cosmology	Sociology/Economics/Politics
Level 9:	Astronomy	Psychology
Level 8:	Space science	Physiology
Level 7:	Geology, Earth science	Cell biology
Level 6:	Materials science	Biochemistry
Level 5:	Physical Chemistry	Chemistry
Level 4:	Atomic Physics	Atomic Physics
Level 3:	Nuclear Physics	Nuclear Physics
Level 2:	Particle physics	Particle physics
Level 1:	Fundamental Theory	Fundamental Theory

Table 1: *The hierarchy of structure and causation for inanimate matter (left) and for life (right).* For a more detailed description of this hierarchical structure, see <http://www.mth.uct.ac.za/~ellis/cos0.html>.

2.3 Inter level relations

It is useful to characterize causation in this hierarchical context as proceeding in both a bottom-up and a top-down manner [27].

2.3.1 Bottom-up Effects

Causation takes place from the lower to the higher levels of the hierarchy, leading to the emergence of structure and complexity. Often there is *coarse-graining* of lower level variables (e.g. particle states) to give higher level variables (e.g. density and pressure) [4], accompanied by a conversion of usable to non-usable energy when some energy is hidden in lower level states, and hence not manipulable via higher level variables.

2.3.2 The emergence of higher level behavior

Consequent on bottom up causation, higher level behavior emerges from that at the lower levels. Consider how higher level behavior relates to lower level behavior in two adjacent levels in the hierarchy of complexity (Diagram 1). The dynamics of the lower level theory maps an initial state i to a final state f . Coarse graining the lower level variables, state i corresponds to the higher level state I and state f to the higher level state F ; hence the lower level action $t : i \rightarrow f$ induces a higher level action $T : I \rightarrow F$. A *coherent higher level dynamics* T emerges from the lower level action t if the same higher level action T results for all lower level states i that correspond to the same higher level state I [27], so defining an *equivalence class* of lower level states that give the same higher level action [6] (if this is not the case, the lower level dynamics does not induce a coherent higher level dynamics, as for example in the case of a chaotic system). Then on coarse graining (i.e. integrating out fine scale degrees of freedom), the lower level action results in an emergent higher level dynamics: the effective theory at the higher level.

Level $N + 1$:	Initial state I	<i>Higher level theory</i> $T: \Rightarrow$	Final state F
	\uparrow	<i>Coarse grain</i>	\uparrow
Level N :	Initial state i	<i>Lower level theory</i> $t: \Rightarrow$	Final state f

Diagram 1: *The emergence of higher level behaviour from lower level theory. Coarse-graining the action of the lower-level theory results in an effective higher level theory.*

2.3.3 Top-down effects

Once such higher level structures have emerged, they then exert a top-down causal influence on their components [29]. This enables true complexity to emerge through feedback loop between higher and lower levels. It should be emphasized here that this occurs between any two neighbouring levels in the hierarchy; there may or may not be a highest or lowest level (or at least a known lowest level).

In [29] I made the case that *top-down influences play a key role in the way quantum theory works*, particularly as regards both decoherence and state preparation. This paper makes the case that top-down influences are also key as regards the arrow of time. In addition to bottom-up causation, *contextual effects* occur whereby the upper levels exercise causal influences on lower level states by setting the context and boundary conditions for the lower level actions. This underlies the emergence of effective laws of behaviour at higher levels, enabling one to talk of existence of higher level entities in their own right. They then play an effective role not only at their own levels, but also influence the lower

levels by setting the context for the lower level interactions [27].

The key feature underlying top-down causation is thus the *multiple realizability of higher level states*. In a gas, many lower level molecular states s_i correspond to a specific higher level state \mathcal{S} characterized by a temperature T , volume V , and pressure p . These are the effective macroscopic variables; one can ordinarily only access the gas by manipulating higher level variables, hence one cannot determine which specific lower level state s_i realizes the chosen higher level state \mathcal{S} . The number of lower level states that correspond to a specific higher level state determines the entropy of that state [74].

2.3.4 Adaptive Selection

A key case of top down causation is adaptive selection [60, 41]. Here, selection takes place from an ensemble of initial states to produce a restricted set of final states that satisfy some selection criterion. Random variation influences the outcome by providing a suite of states from which selection is made in the context of both the selection criteria and the current environment [55]. *This is the basic process whereby information that is relevant in a specific context [84] is selected from a jumble of irrelevant stuff*; the rest is discarded. This enables an apparent local violation of the second law of thermodynamics, as in the case of *Maxwell's Demon* ([37]:46-5, [63], [1]:4-6; [12]:186-189, 196-199) – who is indeed an adaptive selection agent, acting against local entropy growth by selecting high-energy molecules from a stream with random velocities approaching a trap-door between two compartments (Figure 1c). The selection criterion is the threshold velocity v_c deciding if a molecule will be admitted into the other partition or not.

2.4 The central proposal

Following [28], a basic standpoint will be adopted (Section 2.4.1) and then a central proposal made as to the way the different levels relate to each other (Section 2.4.2).

2.4.1 A Basic Standpoint

I adopt the following starting point for what follows:

BASIC PREMISE: *Individual Events Happen.*

Each aspect is important:

Individual: Statistics is not enough. An ensemble of events is made up of individual events. There is no ensemble if individual events don't separately happen.

Events: Specific things occur. Universal laws describe multifold possibilities of what might happen, but we experience specific events in our own particular history.

Happen: They occur in time: they are about to occur, they occur, then they have occurred. Uncertainty about what might occur changes to the certainty of what has occurred.

Any theory adopted must recognize that this is the case. Theories that deal only with statistics of what happens are incomplete.

2.4.2 Proposal: Nature of physical reality

The view proposed in [29] on the nature of physical reality is as follows.

1. **Combinatorial structure:** *Physical reality is made of linearly behaving components combined in non-linear ways.*
2. **Emergence:** *Higher level behaviour emerges from this lower level structure.*
3. **Contextuality:** *The way the lower level elements behaves depends on the context in which they are imbedded.*
4. **Quantum Foundations:** *Quantum theory is the universal foundation of what happens, through applying locally to the lower level (very small scale) entities at all times and places.*
5. **Quantum limitations:** *Linearity at higher (larger scale) levels cannot be assumed, it will be true only if it can be shown to emerge from the specific combination of lower level elements.*

The same basis will be adopted here.

3 The arrow of time

A key issue for fundamental physics is the determination of the arrow of time. Section 3.1 explains the problem, and Section 3.2 considers basic approaches to its resolution: by coarse graining (Section 3.2.1), by statistical fluctuations (Section 3.2.2), by a foundational quantum arrow of time (Section 3.2.3), and by special initial conditions (Section 3.2.4). The latter seems the viable way to go, and section Section 3.3 develops it in terms of the *Past Hypothesis* – the idea that global conditions determine the arrow of time by top-down causation. Three possible Interpretations of this idea are distinguished, and then pursued in the subsequent sections.

3.1 The issue

A crucial aspect of the relation between macro and micro physics is the origin of the arrow of time ([21]:68-80) : one of the major puzzles in physics. There is a profound disjunction between macro and micro physics in this regard.

At the macroscopic scale, the Second Law of Thermodynamics is an unavoidable physical reality [21]: the entropy S of isolated systems increases with time:

$$dS/dt \geq 0, \tag{7}$$

with equality only in equilibrium cases. Classic examples are

- gas in one half of a container spreading to fill the whole when a partition separating it from the other half is removed (Figures 1(a), 1(b)),
- a glass falling off a table and smashing to pieces,
- water flows downhill,
- a block sliding on a plane and coming to a stop owing to friction,
- a stone tossed into a lake and sending out waves along the surface of the water,
- a radio signal or sound wave is received after it was sent,
- a footprint left in the sea sand after you have walked past,
- the moving finger writes and moves on, leaving its trace behind (Omar Khayam),
- the progress of life from birth to death: the seven ages of mankind (Shakespeare).
- the evolution of life on earth: once there was no life, now there is;
- the progression of structure growth in the universe: once there was no structure; now there is.

Thus the arrow of time and irreversibility of physical effect occurs on all scales of the hierarchy, except perhaps the quantum scale; but it occurs there too if one accepts the reality of wave function collapse (7).

This irreversibility relates to **loss of useable energy** as the passage of time occurs, and associated **increase of disorder** ([12]:143-171). It is a core feature of thermodynamics [40] and physical chemistry [5], and hence plays a crucial role in biology ([11]:143-144), energy flows in ecosystems [90, 101], and energy needs of an industrial economy [43].

At a microscopic level, with one caveat I attend to shortly, the basic interaction equations for the four fundamental forces are time symmetric, and so coarse graining them should lead to time symmetric macroscopic laws. The unitary evolution described by the quantum evolution equations also does not determine a direction of time, because the underlying unitary theory treats the future and past directions of time as equal. Specifically: in equation (4), one can make the swap $t_1 \leftrightarrow t_2$ and get an identical solution to (4), but with the opposite arrow of time. The same is famously true of Feynman diagrams.

3.1.1 The micro-macro relation

Macro effective laws are determined by coarse-graining micro laws (Section 2.3.2). *The macro laws that emerge by coarse graining should have the same time symmetry as the micro laws* (simply reverse the arrow of time in the coarse graining process in Diagram 1). This is true even when we deduce higher level equations for irreversible statistical behaviour: there will be an equally good solution with the opposite direction of time. Hence there is apparently a fundamental contradiction:

The macro behaviour displays a time asymmetry that is not apparent in the fundamental equations out of which they emerge.

Thus for each solution of the equations of Newtonian dynamics, of Newtonian gravity, of electromagnetic theory, of special relativity there is a time reversed solution of the equations where everything happens in the opposite sense of time. In the case of the glass falling off a table and smashing to pieces, there is a time reversed solution where the pieces of the glass assemble themselves into a whole glass and ascend back onto the table [71]. In the case of the water waves, there is a time reversed solution where spherical incoming waves converge on a point and pull the stone back up out of the water [105]. But we never see this happen in practice.

The basic problem: *How does the macro theory determine which is the future as opposed to the past, when this time asymmetry is not apparent in the underlying unitary theory?* [34, 18, 105, 48, 10].

The caveat mentioned above is that there is a very weak time asymmetry of weak interactions. However this seems too ineffective to be the origin of the time asymmetry we see at macroscales: the weak interaction does not have enough purchase on the rest of physics (indeed it is very difficult to detect).

3.2 Possible resolutions

This Section considers in turn resolution by coarse graining, by statistical fluctuations, by a foundational quantum arrow of time, and by special initial conditions. The first three are bottom-up approaches that all cannot succeed because of Loschmidt's paradox (Section 3.2.1). Hence a top down approach - special cosmological initial conditions - has to be the way to go (Section 3.2.4).

3.2.1 Bottom-up resolution by coarse graining

Now an initial reaction is that coarse graining from micro to macro scales results in an arrow of time, as shown beautifully by Boltzmann's H-Theorem ([105]:43-48), resulting from the fact that random motions in phase space takes one from less probable to more probable regions of phase space ([73]:686-696; [42]:43-47; [12]:172-174) [74]:9-56). Hence one can show that entropy increases to the future; the second law of thermodynamics at the macro level emerges from the coarse grained underlying micro theory. The quantum theory version of this result is the statement that the density matrix open open system evolves in a time asymmetric manner, leading to an increase in entropy ([8]:123-125).

But this apparent appearance of an arrow of time from the underlying theory is an illusion, as the underlying theory is time symmetric, so there is no way an arrow of time can emerge by any local coarse graining procedure. Indeed the derivation of the increase of entropy in Boltzmann's H-Theorem applies equally to both directions of time (swap $t \rightarrow -t$, the same derivation still holds).

This is Loschmidt's paradox ([71]: Fig 7.6; [73]:696-699; [74]):

The H-theorem predicts entropy will increase to both the future and the past.

(Figure 2). The same will apply to the quantum theory derivation of an increase of entropy through evolution of the density matrix ([8]:123-125, [42]:38-42, 53-58): it cannot resolve where the arrow of time comes from, or indeed why it is the same everywhere.

The latter is a key question for any local proposal for determining the arrow of time:

The arrow of time locality issue: *If there is a purely local process for determining the arrow of time, why does it give the same result everywhere?*

We are unaware of any contradictions as regards the direction of the arrow of time, either locally (time does not run backwards anywhere in Earth) or astronomically (irreversible process in distant galaxies seem to run in the same direction of time as here [80]). Some coordinating mechanism is called for.

3.2.2 Bottom-up resolution by statistical fluctuations

If one has an equilibrium state that last an infinite time, fluctuations round equilibrium can lead to any state whatever popping out of the vacuum just as a statistical fluctuation, with emergence of a local arrow of time. This leads to Poincare's *Eternal return* (any state whatever that has occurred will eventually recur) and the *Boltzmann Brain* scenario: you can explain the existence of Boltzmann's brain not as a result of evolution but just as an eventual inevitable result of statistical fluctuations if an infinite amount of time is available ([12]:201-227).

In the real universe we have not had an infinite time since the start of inflation, and have not had statistical equilibrium anywhere except for very short timescales in very local contexts. And it would also run into the locality issue (Section ??): such fluctuations would be local in space, and different arrows of time could emerge in different places. The context for relevance of these arguments has not occurred in the real universe: the argument does not take realistic context into account ([37]:46;[105]:42), except possibly in the far future of the universe if it expands forever due to a cosmological constant ([12]:313-314). It cannot explain the arrow of time we experience at the present moment.

And even in the case of the far future universe, when we might eventually end up in a de Sitter vacuum state where quantum fluctuations are the only interesting things left, one is entitled to be skeptical about the claims in the Boltzmann Brain literature of pianos, rabbits, and brains popping up out of the vacuum. This is quite different from what is described in quantum field theory texts, where "quantum mechanics and special relativity inevitably cause particles to pop out of the vacuum and they could even interact before vanishing again into the vacuum" ([104]:57-59). This fleeting appearance of particles from the vacuum is far cry from any macroscopic objects emerging - there is certainly no claim in standard quantum field theory texts [36, 58, 104, 75] that given sufficient time, macro objects will emerge. One can suggest that the Boltzmann Brain discussion does not take realistic mechanisms into account. It may not ever be relevant to the real universe.

3.2.3 Bottom up resolution by a foundational quantum arrow of time

Could a resolution come from the local time asymmetry in state vector projection (7)? After all if quantum physics underlies all the rest, perhaps the time asymmetry involved in (7) could be the source for the rest, based in the way a local emergence of classicality works through collapse of the wave function ([73]:527-530; [1] 136-147) and associated increase of entropy [106]. But then where does that quantum level time asymmetry come from? That depends on the resolution of the unresolved issue of state vector reduction. I will make the case that the nature of this process is determined by local top-down effects (Section 2.3.3) due to the specific nature of local physical structures [29]. In that case, this asymmetry may be determined locally by top-down causation, rather than being the source of the asymmetry. This conclusion is reinforced by the the locality issue (Section ??): in order to assign an arrow of time everywhere in a consistent way, it has to be determined contextually through some coordinating mechanism ensuring it is the same everywhere in a connected spacetime domain.

The likely solution is that resolution is by a top-down effect, the local time asymmetry of state vector reduction being based in a time asymmetry in the local detection environment, in turn founded in conditions in the universe as a whole: the local environment too has to know which time direction to choose as the future, else the set of local environments too will fall foul of the locality issue. The issue arises for each level in the hierarchy of complexity (Table 1): if it is not determined from below, it must be determined from above. Considering higher and higher levels, the answer must lie at the top.

3.2.4 Resolution by initial conditions

The implication must be that the arrow of time results from global environmental conditions, as it can't reliably emerge in a consistent way from local physics that does not care about the direction of time. Feynman stated in his lectures,

“So far as we know all the fundamental laws of physics, like Newton’s equations, are reversible. Then where does irreversibility come from? It comes from going from order to disorder, but we do not understand this till we know the origin of the order... for some reason the universe at one time had a very low entropy for its energy content, and since then the entropy has increased. So that is the way towards the future. That is the origin of all irreversibility, that is what makes the process of growth and decay, that makes us remember the past and not the future...” ([37]:46-8)

This fits into the fundamental nature of causality in the following way: a key feature of causality as determined by physical equations is that (cf. [51];[105]:1-3) the outcome depends both on the equations plus the initial and/or final conditions. Hence

Broken symmetry: *The solution of a set of equations will usually not exhibit the symmetry of the underlying theory. If there is no time asymmetry in the equations, it must lie in the initial and/or final conditions.*

Note that precisely because we are dealing with time asymmetry, we cannot assume it is the initial conditions alone; we may need to compare them to final conditions ([99]; [71]). However I will make the case below that we need to be concerned only with initial conditions.

3.3 Top-down determination: The Past Hypothesis

Thus the only viable option seems to be the *Past Hypothesis* ([2]; [12]:176):

The direction of time must be derived by a top-down process from cosmological to local scales.

It is strongly supported by the fact that the entropy of universe could have been much larger than it was ([71]; [12]:345-346) because black holes could have had much more entropy ([12]:299-302; [73]:728-731)). It started off in a very special state, characterized by the Weyl Curvature Hypothesis (The universe is asymptotically conformally flat at the big bang ([73]:765-769)), which was required in order that inflation could start [72].

To investigate this further, I distinguish the following three possible aspects:

- **AT1: Global time asymmetry:** a difference in conditions at the start and end of the universe ([99], [38]:28-6, [34]);
- **AT2: Global past condition:** Special conditions at the start, on cosmological scale: the expanding universe started in a special low entropy condition,¹ which thus made it possible for it to evolve towards higher entropy states ([73]:702-707, [12], [74]:57-136)) and solves Loschmidt's paradox (Figure 2). That is, the global past condition cascaded down to give a sequence of local past conditions.
- **AT3: An initial master arrow of time:** the other arrows derive from the global master arrow of time resulting from the universe's early expanding state. The arrow of time at the start is the time direction pointing away from the initial singularity; this then remains the direction of time at all later times.

Such cosmological asymmetries provide a possible source determining why the local arrow of time is the way it is, by top-down causation from the global to the local direction of time (the latter will therefore be the same everywhere). But this general idea has to be made more specific in relation to the various local arrows of time: thermodynamic, electrodynamic, gravitational, quantum, and biological [34, 18, 105, 48].

By looking at such specific cases, I will make the case that **AT1** is not the way to go, because the proper context to view the situation is an evolving block universe (Section 7), which rules this proposal out. Rather the direction of the arrow of time is due to a combination of **AT2** and **AT3**: the former sets the conditions for the flow of time, and the latter provides the direction of time.

¹Arrow of time arguments are notoriously tricky. If you consider the arrow going the other way, then this state would be the end, not the start.

4 The start and continuation of time

To look at this, we must have a reasonable model of cosmology from some starting time through structure formation up to the present day [50, 93, 19, 31]. Section 4.1 shows how cosmic time is set up, Section 4.2 discusses the main relevant cosmic epochs since the start of inflation, and Section 4.3 the speculative pre-inflation possibilities.

4.1 Cosmic time

The background model used in cosmological studies is the Friedmann-Lemaître-Robertson-Walker (FLRW) spacetime, given in comoving coordinates by

$$ds^2 = -dt^2 + a^2(t)d\sigma^2 \quad (8)$$

where $d\sigma^2$ is a 3-space of constant curvature and $a(t)$ the scale factor [54, 26, 31]. Perturbations around that model characterize how structure formation took place [19, 31].

The dynamics of the FLRW model is governed by three interrelated equations. The *energy-density conservation equation* determines the time evolution of the density $\rho(t)$:

$$\dot{\rho} + (\rho + p/c^2)3\frac{\dot{a}}{a} = 0. \quad (9)$$

and so determines the evolution of the pressure $p(t)$ through a suitable equation of state $p = p(\rho)$. Second, the scale factor $a(t)$ obeys the *Raychaudhuri equation*

$$3\frac{\ddot{a}}{a} = -\frac{1}{2}\kappa(\rho + 3p/c^2) + \Lambda, \quad (10)$$

where κ is the gravitational constant and Λ the cosmological constant. Third, the first integral of equations (9, 10) when $\dot{a} \neq 0$ is the *Friedmann equation*

$$\frac{\dot{a}^2}{a^2} = \frac{\kappa\rho}{3} + \frac{\Lambda}{3} - \frac{k}{a^2}. \quad (11)$$

where k is an integration constant related to the spatial curvature. Thus the cosmic time is the time parameter t that enters into these equations determining the scale factor evolution. It is determined by being the time parameter naturally appearing in the 1+3 covariant formulation of the Einstein Field equations in the cosmological context [31], which reduce to equations (9)-(11) when specialized to a FLRW geometry.

Classically, the universe began at a spacetime singularity [54], conventionally set to be $t = 0$. Cosmic time starts at the creation of universe: time came into being, it did not exist before (insofar as that makes sense). After then there is no way it can reverse. Once it is established it just keeps rolling along, determining what happens according to (9)-(11) unless we reach a spacetime singularity in the future, when it comes to an end.

The cosmological arrow of time is set by the start of the universe.

There is no mechanism that can stop or reverse the cosmological flow of time, set by the start of the universe. It sets the direction of time, which starts at $t = 0$ and then increases monotonically, being the parameter t occurring in the solution $\{a(t), \rho(t), p(t)\}$ to equations (9)-(11).

This is the master arrow of time **AT3**. The gravitational equations (9)-(11) are time symmetric (because the Einstein equations are time symmetric), but the actual universe had a start. This broke the time symmetry and set the master arrow of time: the universe is expanding, not contracting.

How this evolution actually occurs is determined by the changing equation of state of the universe at different epochs (next section). When we take account of quantum gravity, this picture is altered, and various options arise ([24]:16-18); these are discussed below in Section 4.3. However the universe will still set a unique monotonically increasing time for all epochs after the end of the quantum gravity epoch.

4.2 The cosmic epochs

The basic dynamics of cosmology to the present time can be regarded as having five phases ([19]:1-20),² summarized in Figure 3:

- **Epoch 0: Pre-Inflationary era.** Any quantum gravity era that might precede inflation. The dynamics at this time is hypothetical: we don't know what happened then (there may or may not have been an actual physical start to the universe).
- **Epoch 1: Inflationary era.** A very brief period of exponential expansion, ending at reheating and conversion of the inflaton field to radiation, marking the start of the Hot Big Bang era. Inflation is the time when quantum perturbations arose that provided the seeds for structure formation at the end of the Hot Big Bang era.
- **Epoch 2: Hot Bang era.** Epoch of Radiation and Matter in quasi-equilibrium, up to the time of decoupling of matter and radiation at the *Last Scattering Surface* ('LSS'). This epoch includes baryosynthesis, nucleosynthesis, and the transition from a radiation dominated to matter dominated expansion. The universe was opaque up to the end of this era.
- **Epoch 3: Structure formation era.** From the LSS to the present day. The universe became transparent, matter and radiation decoupled leading to the universe being permeated by Cosmic Black Body Radiation (CBR), and structure formation commenced, leading to the existence of large scale structures, galaxies, stars, and planets. At a late time (close to the present day) dark energy started to dominate the dynamics, leading to a speed-up of the expansion of the universe.
- **Epoch 4: The future.** From the present day on, either an unending expansion (the most likely option), or recollapse to a future singularity; which is the case depends on parameters and physics that is not well known.

The dynamical behaviour is different in each epoch. To a good approximation we can represent the inflationary era, radiation dominated era, and matter dominated era as

$$\text{Inflation : } p = \rho c^2 \Rightarrow a(t) = a_0 e^{H(t-t_0)} \quad (12)$$

$$\text{Radiationdominated : } p = \frac{1}{3}\rho c^2 \Rightarrow a(t) = a_1 (t - t_1)^{1/2} \quad (13)$$

$$\text{Matterdominated : } p = 0 \Rightarrow a(t) = a_2 (t - t_2)^{2/3} \quad (14)$$

²See [26]: Sections 2.1-2.2, 2.6-2.8 for a conveniently accessible short description.

Dark energy started to be significant late in Epoch 3, altering (14) a bit at late times, but it only alters the big picture significantly in the future era (Epoch 4), where it suggests there will be no final singularity: expansion will last for ever.

These different epochs will be revisited in Section 5.

4.3 The speculative pre-inflationary era

What previous mechanism could lead to a universe satisfying the past condition? Why is the universe an almost-FLRW universe when it emerges from the inflationary era? What set the conditions before inflation such that inflation could start?

We are in a domain of untestable speculation here, and the possibilities we can imagine certainly won't encompass all that might have been the case. Still it's fun to speculate. The problem is to find a way that generates a smooth start to the universe, given that inflation can't do so for generic initial conditions [71, 72]. Amongst the possibilities are,

- **The smooth universe machine** Whatever creates the universe makes a nice smooth universe: it works in a uniform way at all emergent spacetime events. This was the assumption everyone made from the 1930s until the 1970s [50].
- **The multiple universe machine** Whatever creates the universe keeps doing it, with variation. This includes the chaotic inflation scenario. Both arrows of time can occur in different domains ([12]:359-364, 371-372;[13]).
- **The bounce machine** The present epoch of the universe resulted from some kind of bounce or rebirth from a previous era that sets up the special state needed ([12]:349-353; [74]).
- **The emergent universe machine** Whatever creates the universe makes an emergent universe that spends a long time in an almost static state, with compact spatial sections [30, 32, 68]. The previous state does not matter as there is plenty of time for matter to come into equilibrium: causal effects can travel round the universe thousands of times.
- **The quantum gravity machine** Whatever creates the universe does so in a quantum gravity era where causality has not yet emerged, for example there is a space-time foam, so causal restrictions don't yet exist. Horizons emerge later.

Whatever happened in this era is the ultimate source of the arrow of time, but the physics is completely uncertain, as is the overall context. I will here assume that whatever was needed happened, and led to a suitable start of inflation.

5 The descent of time: contextual effects

The basic idea in this section is that the expansion of universe determines the arrow of time at lower levels in the natural sciences hierarchy. Crucially, at the beginning of the

HBB era the universe was expanding and cooling, not vice versa. This sets the arrow of time for local physics. This occurs in the inflationary epoch (Section 5.1), the hot big bang era (Section 5.2), and the astronomical epoch (Section 5.3). This determines the local thermodynamic arrow of time (Section 5.4) and the radiative arrow of time (Section 5.5). To do examine the latter clearly, it is useful to introduce the idea of a finite infinity for isolated systems (Section 5.5.2). Finally the arrow of time cascades down from local systems to microsystems (Section 5.6).

5.1 Epoch 1: Inflation

This exponentially expanding era (12) is driven by a scalar field called the inflaton ([93]:115-123). It has three effects:

- The exponential expansion causes initial inhomogeneities and curvature to decay away ([19]:144-155).
- Quantum fluctuations generate tensor perturbations that result in gravitational waves ([19]:155-162).
- Quantum fluctuations generate scalar perturbations that result in density inhomogeneities that later on are the seeds for large scale structure formation ([19]:162-173).

These effects all evolve in the forward direction of time that underlies the expansion occurring then (Figures 6.7 and 6.8 in [19]). It is this expansion and arrow of time that sets the context for these important physical effects, being an example of **AT3**. However the inflation would not start if the universe at the beginning of the inflationary epoch was not of limited anisotropy [86] and inhomogeneity [72] (an example of **AT2**).

Inflation ends at reheating, when the inflaton gets converted to radiation. This sets the almost homogeneous initial conditions for the next stage.

5.2 Epoch 2: The Hot Big Bang Era

In the Hot Big Bang epoch, there was a heat bath with matter, photons and neutrinos ([19]:40-46) mainly in equilibrium at a temperature T that decreases with time. The early part of this epoch is radiation dominated, but it becomes matter dominated before last scattering ([19]:50-51). In the early radiation dominated era, the scale factor goes as (13) and the temperature drops as ([19]:4-5)

$$T(t) = \frac{a(t_0)}{a(t)} T_0 \propto \frac{T_0}{(t - t_1)^{1/2}}. \quad (15)$$

This sets up a context which provides the arrow of time for local reactions: the time symmetry is broken by the steady drop in temperature of the heat bath that is the time-changing environment for local reactions such as nucleosynthesis.

The expansion of a equilibrium hot equilibrium mixture of particles and radiation is time reversible (pair production and annihilation, element formation and decomposition

balance) until reaction thresholds are passed so some of these reactions cease and leaves behind out of equilibrium decay products, characterizing irreversible behaviour at those times. The major such non-equilibrium features are

- Baryogenesis processes and the development of an asymmetry between particles and antiparticles ([96]; [93]:134-137; [83]);
- Neutrino decoupling, neutron decoupling, and the formation of light elements at the time of nucleosynthesis ([93]:140-143; [19]:9-12,62-70);
- Recombination of electrons and protons into neutral hydrogen, resulting in decoupling of matter and radiation ([93]:162-163; [19]:70-73), so determining the LSS and originating the CBR (photons stream freely from then on);³
- Possibly, production of dark matter ([19]:73-78).

These irreversible processes can all be described by suitable versions of the Boltzmann equation ([19]:59-62;84-113). A crucial feature is

- Growth of perturbations as different comoving scales leave and re-enter the Hubble horizon ([19]:180-213), and baryon-acoustic oscillations take place ([19]:224-230), accompanied by diffusion on some scales ([19]:230-234) and radiative damping of shorter wavelengths ([93]:176-180).

Reversible and irreversible processes in this period have their time arrow set by the expansion of universe which determines how context changes (a time dependent heat bath). This is another example of **AT3**. Initial conditions were special, which also plays a role: for example the expansion rate and hence light element production would be different in very anisotropic or inhomogeneous cosmologies, so this is also an example of **AT2**.

Overall, this epoch serves to prepare special conditions on the LSS, homogeneous to one part in 10^{-5} , which marks the end of this epoch. It occurs when $T_{rad} \simeq 4000K$.

5.3 Epoch 3: The astronomical arrow of time

In this epoch, matter and radiation are initially decoupled, so they are no longer in thermal equilibrium. Radiation pressure (which previously led to the baryon acoustic oscillations) no longer resists gravitational collapse, and structure formation can commence.

Structure formation takes place spontaneously through gravitational instability ([88]: Chapter 21). An initially uncorrelated system develops correlations through gravitational attraction: “Gravitational graininess initiates clustering” ([88]:158-162). There is no arrow of time in the underlying time-symmetric Newtonian gravitational law:

$$m \frac{d^2 x^i}{dt^2} = -\nabla^i \Phi, \quad \nabla^2 \Phi = 4\pi G \rho \quad (16)$$

³There is an earlier process of helium decoupling, which is not as important thermodynamically.

(which derives in the appropriate limit from the Einstein Field Equations). The process attains an arrow of time in the expanding universe context because of the change of equation of state at the LSS: pressure forces that resisted collapse melt away, and structure formation begins from the tiny density inhomogeneities present on the LSS. The arrow of time is provided by the context of cosmic evolution (and is thus a top down effect).

As structure forms *spontaneously* through a bottom up process dominated by cold dark matter ([80]:23-35,39-45; [93]183-186), this process apparently violates the second law of thermodynamics as often stated ([71, 23]; [12]:295-299); see Figure 1d. The entropy law somehow must be consistent, but we do not at present have a viable definition of gravitational entropy for generic situations. In any case it is clear that the process requires special smooth initial conditions so that structure can form: if black holes were already present everywhere, there would be no possibility of further structure formation [71].

Star formation takes place leading to ignition of nuclear fusion and nucleosynthesis in stellar interiors ([93]:301-331;339-345). The CBR ([93]:75-81) is now collision free, so its temperature drops as the inverse of the scale factor ([19]:5):

$$T_{radn}(t) = \frac{a_{LSS}}{a(t)} 4000 K. \quad (17)$$

This is much lower than the stellar temperatures, so the stars can function in thermodynamic terms (they can get rid of heat by radiation to the sky). The many irreversible astrophysical processes [80, 92] leading to the evolution of stars ([93]:202-204, 229-231, 288-298) and galaxies and galaxy clusters ([93]:187-202, 323-327) are based in bottom-up emergence of effective thermodynamical behaviour, but this is possible only because of the non-equilibrium context set by the early universe according to the cosmological master arrow of time. The lowness of the Sun's entropy (remoteness from thermal equilibrium) is because of the uniformity of the gas from which the Sun has gravitationally condensed ([73]:705-707).

Conclusion: Structure formation takes place by irreversible processes starting in the inflationary era, resulting in fluctuations on the LSS that irreversibly lead to stars, galaxies, and planets after decoupling. The arrow of time for these processes derives from the cosmological master arrow of time (Section 5.2).

5.4 Thermodynamic arrow of time: local systems

For local systems on Earth, the arrow of time is apparent in the diffusion equation and in local physical interactions in machines, plants, animals, ecosystems, and the biosphere as a whole ([105]:39-84). This is all possible because we live in a non-equilibrium local environment, which is due to the larger astronomical environment (Section 5.3).

Bright Sun plus dark night sky The Sun is a radiation source which is a hot spot in an otherwise cold background sky. Because of their higher energy, there are many fewer photons coming in from the Sun than those reradiated in the infrared to the sky,

since the total energy carried in is the same as that going out ([71]:415; [73]:705-707; [12]:191-194). The radiation heat balance equation for received solar short wave radiation ([66]:60-61) leads to overall annual, daily and instantaneous heat balances ([66]:71-77) due to the properties of incoming solar radiation ([66]:23-58) and radiative properties of natural materials ([66]:60-71). This leads to the heat balance equations for animals that enables life to function ([66]:150-170). This is all possible because the sky acts as a heat sink for the emitted long wavelength radiation.

The reason the sky can act as a heat sink is the modern version of **Olber's paradox** (why the sky is dark at night? [49], [50]:248-265). The sky is dark because the universe is expanding ([50]:491-506; [93]:55-58), so by (17), the Cosmic Background Radiation has cooled from its temperature of 4000K at the LSS to the present day CBR background temperature of 2.75 ([50]:339-349; [105]:26-27). Star formation since decoupling has made a negligible further contribution: it has led only to an effective temperature of 3K also. This would not be the case if there were a forest of stars covering the whole sky ([50]: Figure 12.1, p.250), when every line of sight would intersect a star and the temperature on Earth would be the same as on the surface of a star. Thus we are in a thermal bath at 3K as a result of expansion of universe and its subsequent thermal history, resulting both in cooling of the CBR to 2.73K and in stars only covering a very small fraction of the sky. This astronomical context underlies the local thermodynamic arrow of time.

Example: Broken glass A classic example is a glass falling from a table and lying shattered on the floor (Penrose [71]:397-399). Because the underlying micro-dynamics is time-reversible, in principle it can be put together again by just reversing the direction of motion of all the molecules of the glass and in the air and the floor: it should then jump back onto the table and reconstitute itself. But this never spontaneously happens. Why is the one a natural event and the other not?

It does not spontaneously reverse and reconstitute itself firstly because this is fantastically improbable: the asymmetric increase of entropy, due to coarse graining, prevents this ([71]:391-449); and that is because of special conditions with correlations (the crystal structure) in the initial state that don't occur in the final state. Secondly, you can't reverse it at room temperature because of the thermodynamic threshold required to make the glass. It requires a temperature of about 1140C to recreate this crystal structure (making a glass requires a furnace); but destroying it's brittle structure (due to its particular atomic configuration) can naturally take place at room temperature. The cold night sky keeps us below this temperature and so stops this reconstitution happening naturally. Indeed if the sky were covered by a forest of stars, you could never make the glass in the first place; the night sky (and day sky) would be at the temperature of the surface of a star, so apart from the fact that you would not exist, the only form of glass possible would be molten. Similarly stars can only function because of the dark night sky: like the biosphere, they too could not get rid of their excess energy to the sky if the sky were everywhere as bright as the surface of a star.

5.5 Isolated systems and the Radiative arrow of time

There is a further important issue: the relation between the radiative arrow of time and the thermodynamic arrow of time [34]. Consider first water waves spreading out, consequent on a stone being thrown into a pond. In principle, because of the time reversible microphysics, one can reverse the direction of time to see the waves focus in and make the stone pop out of water. In practice this can't be done. Again, we have a **resolution by asymmetric correlations**: typical incoming waves are not correlated, but the outgoing waves are (they diverge from one point). Thus the arrow of time is reflected in the asymmetry of correlations in the future relative to the past.

But is this asymmetry a cause or an effect? Suppose we don't want to talk about the future: can we just talk about special initial conditions in the past? Yes, this should be possible: all we need is the structure of phase space ([71]:402-408) plus special conditions in the past ([71]:415-447). One does not need a future condition. But one does need the past condition *on the relevant scale* (it is needed on the scale of stars for the astrophysical arrow of time, but on the scale of molecules for the arrow of time in water waves). Hence we need a

Local Past Condition (LPC): *special initial data occurred at the relevant scale for the phenomenon considered.*

The initial conditions that lead to structure are less likely than those that don't, but they did indeed occur in the past. This **LPC** applies at the scale relevant to broken glasses and unscrambling eggs because it has cascaded down from the cosmological scale to the local scale. This incoming and outgoing asymmetry applies to water waves, sound waves in the air, and elastic waves in solids. It applies on the astronomical scale to supernova explosions: one can in principle reverse direction of time to see the outgoing radiation focus in and the supernova reassemble; in practice this cannot happen because of the very special initial conditions required for the time reverse motions to do this.

5.5.1 Electromagnetic waves

The same issue arises for electromagnetic radiation, indeed this is *the* relevant case as regards the heat from the Sun because that arrives as radiant energy. Why does it come from the past null cone rather than the future null cone, given that Maxwell's theory is time symmetric? And why do radio signals arrive after they are sent, rather than before? The answer is similar to that for acoustic waves: there is a fundamental difference between incoming and outgoing electromagnetic radiation, in terms of coherence on the future null cone as compared with the past. But then why is that so? It derives from cosmic initial conditions, cascading down from larger to smaller scales. To look at this properly, we need to be clearer on the spacetime domains involved.

5.5.2 Isolated systems: The relevant domains

We need to consider an effectively isolated system, such as the Solar System (see Figure 3: as explained in the Caption, this is in conformal coordinates, with matter world lines vertical lines). *The Earth's world line* is at the centre, the event '*here and now*' is where

the present time intersects our world line. The incoming light cone (to the past) intersects the LSS on a 2-sphere, which I call the *CMB sphere*, because this is the part of the LSS that emitted the radiation we today measure as 2.73K Cosmic Black Body Radiation (the CMB sphere has been mapped in detail by the WMAP and Planck satellites). The *Visual Horizon* is formed by the matter world lines through the CMB sphere (we cannot see any matter further out by any electromagnetic radiation). Hence the whole visible universe lies between our world line and the visual horizon, from the LSS till today (strictly: from the LSS to our past light cone, but we can extrapolate to today). On these scales we can extrapolate to the future, but with increasing uncertainty the further we extrapolate towards the final future events.

To examine the relation between incoming and outgoing radiation, one can use the idea of **Finite Infinity** $\mathcal{F}i$ [22]. We surround the system S of interest by a 2-sphere $\mathcal{F}i$ of radius $R_{\mathcal{F}i}$ such that it is at infinity for all practical purposes: spacetime is almost flat there, because it is so faraway from the source at the centre, but it is not so far out that the gravitational field of other neighboring objects is significant. For the Solar System, R_f is about 1 light year; for the Galaxy, 1 Mpc. The world tube marked out by $\mathcal{F}i$ is shown in Figure 3; we can examine the interaction of the local system with the rest of the universe by considering incoming and outgoing matter and radiation crossing this world tube.

The intersections of our past light cone C^- with $\mathcal{F}i$ gives a 2-sphere \mathcal{C}^- a distance $R_{\mathcal{F}i}$ away which is our effective sky; all incoming radiation crosses \mathcal{C}^- . Similarly the 2-sphere \mathcal{C}^+ defined by the intersection of our future light cone with $\mathcal{F}i$ is our future sky; all outgoing radiation crosses \mathcal{C}^+ . The arrow of time has two aspects. First, it lies in the difference between data on \mathcal{C}^+ , which has high correlations with our position due to outgoing signals from the Earth, whereas that on \mathcal{C}^- does not have time-reversed similar correlated incoming signals focussed on the Earth. Second, it lies in the fact that the amount of incoming radiation on \mathcal{C}^- is very low; this is the dark night sky condition mentioned in the previous section. It is in effect the Sommerfeld incoming radiation condition ([105]:23).

The reason there is little radiation coming in on \mathcal{C}^- , and that it is uncorrelated to a high degree, is two-fold. Firstly, there is a contribution from data on the CMB sphere region of the LSS, which is almost Gaussian, and then is diluted by the cosmic expansion from 4000K to 2.75 K (see above). Second, the intervening matter between the LSS \mathcal{C}^- is almost isotropic when averaged on a large enough scale, and luminous matter covers a rather small fraction of the sky (we do not see a forest of stars densely covering the whole sky); hence we receive rather little light from all this clustered matter (stars in our galaxy, all other galaxies, QSOs, etc).

But how does this relate to solutions of Maxwell's equations in terms of advanced and retarded Green's functions ([105]:16-38)? And why does matter here, and the intervening matter, emit radiation to the future rather than the past? This is allowed by thermodynamic constraints on the emission processes; but this does not by itself explain the electrodynamic arrow of time. Why does a shaken electron radiate into the future and not the past? We need a condition where the waves generated by a source are only waves that go outward, so only the outgoing wave solution makes physical sense ([38]:20-

14). I suggest that the reason is that only the past Green's function can be used in such calculations, because we live in an *Evolving Block Universe* (EBU): we can't integrate a Green's function over a future domain that does not yet exist. This is discussed in Section 7. The Local Past condition **LPC** is needed on these scales so that thermodynamic and associated electrodynamic processes can take place in the forward direction of time; but the EBU is the ultimate reason that time goes to the future and not the past.

5.5.3 Incoming and outgoing matter

As well as radiation, an isolated system is subject to incoming and outgoing matter. There are two aspects here. First, the matter that made up the solar system and nearby other systems – indeed the matter out of which we are made — originated within our **matter horizon** [35], a sphere with comoving radius of about 2 Mpc, lying between $\mathcal{F}i$ and the visual horizon (Figure 4). The intersection of the matter horizon with the LSS (see [35] for a discussion and detailed spacetime diagram) is the domain where we require special past conditions to be true in order that the solar system can arise from astrophysical processes with the forward arrow of time. This is the **LPC** for the Solar system.

Second, there may be incoming particles (cosmic rays, black holes, asteroids, comets) crossing $\mathcal{F}i$ since the solar system formed and impacting life on Erath. These too must be of low intensity in order that local equilibrium can be established and local thermodynamic processes proceed unhindered. The Local Past Conditions on the LSS in the domain close to the matter horizon will ensure this to be true. We assume this for example in experiments at particle colliders: if there was a huge flux of incoming cosmic rays, we would not be able to do experiments such as at the LHC. Local thermodynamics can proceed as usual because we are indeed an effectively isolated system.

The universe does not interfere with our local affairs: a case of *top-down non-interference* that could have been otherwise: there could have been massive gravitational waves or streams of black holes coming in and interfering with local conditions, as well as high energy photons. Isolated systems are necessary for life ([26]: Section 9.1.3), and the cosmic context sets this local context up suitably.

5.6 Micro systems: quantum arrow of time

The same kinds of considerations hold for everyday physics and local quantum systems. They work in the forward direction of time because of the non-equilibrium local context inherited from the higher level solar system context. If we were in a higher temperature heat bath, there would be different outcomes.

The quantum arrow of time ([105]:85-134) should follow from the local context, because the wave function collapse such as occurs in detectors (based in the photoelectric effect) is due to the local physical context [29]. That context includes the local thermodynamic arrow of time. So for example one can ask why photodiodes or chlorophyll in plant leaves don't behave reversibly: why does a plant not emit light rather than absorbing it, for example? The answer must be that they involve special structures that create

thresholds that general non-unitary behaviour, and the specific arrow of time that occurs is set by prepared initial conditions in the physical apparatus, that make the detector work in the one direction of time, not the other. This is related to the general feature of anisotropic spatial structures plus special initial conditions.

The derived quantum arrow of time is synchronised with the overall system through contextual effects, and in particular decoherence and the Lindblad master equation inherit their arrow of time from the environment. Each is not time reversible because the environment is in a non-equilibrium state (Section 5) and a local asymmetry condition **LPC** applies on micro scales: as in the case of reconstructing a supernova, one could not easily reverse the chemical reactions in photosynthesis, as this would require improbable coordination of incoming entities. The details have to be worked out in each case in relation to the specific physical structures that lead to detection events [29].

6 The ascent of time: basic mechanisms and effects

The existence of time, and the direction of the arrow of time, is taken for granted in applied physics, engineering, biology, geology, and astrophysics. It is assumed as a ground rule that the arrow of time exists and runs unceasingly according to the 2nd law. Given the arrow of time problem as set out above, how does this come about?

The suggestion here will be that the arrow of time that exists at the lower levels (because of the suitable context, as discussed in the previous section) propagates up to higher levels through the process of creation of emergent structures. There are a number of specific emergent mechanisms that enable this to happen, with three related crucial components: arrow of time detectors (Section 6.1), rate of time measurers (Section 6.2), and flow of time recorders (Section 6.3). These are what make the flow of time real. I look at them in turn.

6.1 Arrow of time detectors

If we take series of pictures of objects such as a breaking glass or an exploding supernova, we can discriminate the future from the past by just looking at them: we can order the pictures appropriately. But these aren't regular occurrences that can be used generically to determine the direction of time; there are more systematic ways of doing this.

Generically, a cause precedes its effects; how does one harness this to show which way time is going? The basic principle is

A spatial asymmetry is converted into a time asymmetry through suitable environmental and initial conditions. The requirements are structures with suitable spatial asymmetry, plus special initial conditions.

This is a form of top-down action, due both to the existence of emergent structures, and the link in to the **LPC** discussed above through the requirement of special initial conditions. Specific cases show how this works out in detail.

- **Downhill flow** A rock spontaneously falls down hill, not up; water naturally flows downstream, not up (Figure 5). This applies to *any* energy gradient: exothermic reactions take place spontaneously in chemistry (hence the danger of fires and the need for fire prevention services); electric currents flow from the negative to the positive terminal of a battery, and in electrical and electronic circuits, currents flow towards ground. A natural example is lightning which goes spontaneously to the ground ([37]:9-2 to 9-7). In electronics, forms of electric current include the flow of electrons through resistors or through the vacuum in a vacuum tube, the flow of ions inside a battery or a neuron, and the flow of holes within a semiconductor; they each flow one way as time progresses. A reversed arrow of time would reverse their spatial direction of movement.

Biology is crucially based in the absorption of high energy materials and excretion of low energy waste, the central feature being cellular respiration, based in glycolysis, the citric acid cycle, and oxidation ([11]:160-178). Each of these processes has a forward direction of time that arises out of the underlying physics plus the local context, and so acts as an arrow of time detector.

- **Ratchets** A mechanical ratchet turns one way because of a pawl and ratchet mechanism permitting motion in one direction only as time progresses (Figure 6), thus it is a mechanism for detecting the direction of time as contained in Newtons' law of motion. How does it do it? — it is a mechanism designed to do so! It can only do so when suitable environmental conditions are satisfied: in general Brownian motion takes place, and the pawl can jump out of ratchet allowing it to fluctuate back: when the pawl and are wheel both at the same temperature, the motion is reversible ([37]:46-1 to 46-9). At lower temperatures it is a disguised form of asymmetric sawtooth potential, where diffusion extracts the direction of time from the spatial direction provided by the sawtooth.

Engineering applications include ratchet wrenches and screwdrivers, turnstiles, and hoists. Ratchets are a key mechanism in microbiology: Ref. [91] describes a molecular information ratchet, [85] organic electronic ratchets doing work, and [61] botanical ratchets. Brownian ratchets work by inscribing and erasing an asymmetric potential which induces a directed motion of a particle. Molecular motors are based on biological ratchets [62], and work by hydrolizing ATP along a polar filament.

- **Rectifiers** are devices that make currents flow in only one direction. If you reverse the direction of time, it will go the other way. This works thermodynamically in the case of a vacuum tube rectifier (emission of electrons at a hot electrode and reception at a cooler one). It works by adaptive selection through detailed physical structure of the rectifier, in the case of solid-state rectifiers, taking advantage diffusion currents. In a p-n junction with forward bias, the electrostatic potential in the n-region is lowered relative to p-side, increasing the diffusion current; the pair current is unchanged. The diffusion current exceeds the pair current and there is a net current from the p-side to the n-side; however with a reverse bias this does not happen, hence the junction acts as a rectifier ([20]:997). A mechanical example is a one-way valve in a water system, with a ball and spring in a water outlet into a container. Water flows only in through this valve, not out.

A crucial example of rectifiers in biology is ion channels ([59]:105-124; [81]:219-226; [11]:133-136, 1017-1025). These are pore-forming proteins that establish and control a voltage gradient across the plasma membrane of cells, thereby allowing the one-way flow of ions down their electrochemical gradient. They occur in the membranes that surround all biological cells, for example potassium ion channels (the hERG channel) mediates a delayed rectifier current (IKr) that conducts potassium (K⁺) ions out of the muscle cells of the heart.⁴ All such rectifier functions are based in detailed biological mechanisms (e.g. [44]). These underlie active transport systems in the cell that act like Maxwell's Demon in creating a gradient of K^+ and Na^+ across a cell wall ([64]:191-206).

- **Filters** are devices that select some components of a mixture or ensemble from others, discarding those not selected. The arrow of time is revealed by the process of selection where a subset of the whole emerges as the output (Section 2.3.4). Running it in reverse would generate more states from less, but the final state does not have the information needed to tell what the incoming state was. Examples are polarizers [29], wavelength filters in optics due to selective absorption based in the crystal structure of an optical medium, and tunable radio receivers based in resonance properties of AC circuits ([56]:299-320). Electrical filters can be low-pass, high-pass, or passband filters ([56]:359-385). In biology, excretory processes in organisms are based on a series of filter mechanisms involving selectively permeable membranes and selective reabsorption ([11]:929).
- **Diffusion** is a basic physical process that detects the direction of time: macro-properties of gases naturally smooth out in the future, not the past (Figure 1). Thus diffusion is migration of matter down a concentration gradient ([5]:818). Similarly migration of energy down a temperature gradient underlies thermal conduction, migration of electrical charge down a potential gradient underlies electrical conduction, and migration of linear momentum down a velocity gradient generates viscosity [5]:818). This is a crucial process in chemistry ([5]:817-830,846-856) and thermal physics ([40]:649-654).

Physiological processes often involve diffusion between compartments and through membranes, the direction of time determining the direction of diffusion as an emergent property of the lower level dynamics ([82]:168-220, [81]:116-129). Diffusion plays a key role in capillary systems ([81]:590-592), hormone transport ([81]:373-374), and lungs ([81]:618-619), where it determines action of an anesthetic gas ([82]:312-333). Diffusion is crucial at the synapses connecting neurons in the brain ([11]:139-146, [81]:113-116).

In each case, the macro context acts down on the micro level to induce time asymmetric behaviour arising from spatial gradients (either horizontal, so unaffected by gravity, or with a vertical component, so gravitationally influenced). The macro level dynamics due to inhomogeneities at that level acts down on the micro level to create micro differences (the temperature of a falling rock is hotter at bottom of hill than at top).

⁴See the Wikipedia entry on hERG.

Because this is non-unitary at the macro level, it corresponds to collapse of wavefunction at micro level, for example in the case of water falling down waterfall, each collision of water molecule with a rock is a detection event. There is unitary micro level motion only for very brief periods between collisions. The resulting macro level process is a classical process; there is no superposition at this level.

6.2 Rate of time measurers: clocks and ages

Clocks are direction of time detectors that reliably measure the rate of progress of time, converting it to a linear scale; an integrated clock reading gives an age. Any of the arrow of time detection processes mentioned above can be used as a clock, if it's behaviour is regular enough. Translating it to digital form will always involve non-unitary events.

Dating One can estimate ages of objects by examining historical records, for example in astronomy, archaeology, and geology. Accurate age measurements come from integrating clock readings.

The main methods actually utilized for clocks and dating are as follows. They are interrelated so they are not disjoint, but it is useful to point out the range of specific physical processes at work.

- **Flow in and out of a container** One of the oldest methods is a container with a steady inflow and/or outflow of some quantity, and suitable calibration. It requires a prepared initial state (full or empty) and identifiable final state, when it will require a reset to the initial condition; this is the non-unitary part of the process. Examples are water clocks (filled to the brim and then steadily emptying) and sand funnels (egg timers). One can conversely have a water container that is steadily filled up, and then flushed when full. In electrical circuits, charging and discharging a capacitor is the equivalent ([56]:93-94;108-114).
- **Distance traveled at reliable speed** measures time. An example is an analog clock that rotates its hands at a constant speed through an electric motor drive. The non-unitary part of the process occurs when a dial reading is noted at a specific time by some observer. A sundial is a projection to Earth of such a reliable motion (albeit non-constant: seasonally dependent but predictable corrections must be made). Some forms of clock use the invariance of the speed of light to provide a fundamental basis for timekeeping. A simple example is a *light clock* consisting of an emitter and two mirrors kept a fixed distance apart; the 'ticks' of the clock are the reflection events at one end. The non-unitary part of the process is the reflection events.
- **Counter for repetitive processes** Most current clocks work by counting cycles of some reliable periodic process, like the swing of a pendulum, the cycles of a balance wheel, or the vibration of a quartz crystal. A reader or latch records the cycle, and this analog to digital transformation involves thresholds and so is non-unitary. A computer utilizes a circuit that emits a series of pulses with a precise width and a precise interval between consecutive pulses, made by an oscillator and latch (a circuit that remembers previous values) ([94]:98-103). This is of course a classical

device; with an adder ([94]:96-98), it detects the direction of time and measures the progression of time. It must be based in repeated wave function projection at the quantum level in the transistor gates that underlie its operation ([94]:76-86).

- **Reliable decay processes** Radioactive materials spontaneously decay; the future direction of time is that choice where the amount of radioactivity is less in the future than the past ([37]:5-3 to 5-5). This provides centrally important radiocarbon methods of dating in archaeology ([103]:31-33).⁵ This is a form of the emptying reservoir method mentioned above; state preparation took place in the supernova explosion that created the radioactive elements.
- **Reliable growth processes** can also be used for dating. The classic case (apart from horse's teeth!) is dendochronology: that is dating by counting tree rings ([103]:34). Actually this is really a process of recording the annual cycles of the Earth's motion around the Sun using the tree's developmental processes as the recorder. In astronomy, stellar ages can be determined via stellar evolution theory and observations of the distribution in the Hertzsprung-Russell diagram of cluster stars ([92]:189-193).

All of these measuring processes result as emergent properties of the underlying physics that at some point involves non-unitary evolution (without this feature, the flow of time would be evident in the system dynamics but it could not be recorded).

6.3 Flow of time recorders: records of the past and memory

We are aware of the flow of time because of the existence of records of the past. These are of two types:

Passive records: these are physical records of what happened in the past, such as primordial element abundances, geological strata, palaeomagnetic records, fossils, the genetic code, the nature of biological species, vegetation patterns in the countryside, buildings and infrastructure in cities, and so on. This is *data* which can be used to provide information about the past, when we relate them to some theoretical model.

These data have not been laid down for some purpose; they are just there as remnants of past events. They have not been indexed or classified, but we are able to interrogate them and use them to determine past history, for example in astronomy [92, 93], geology, and biological evolution ([103]:24-35).

Memory records: these are physical records that are a meaningful distillation of what happened, somehow indexed in relation to some classification scheme, so that they can be recovered. This is *information* that can be used for some useful purpose [84].

In both cases, laying down these records of events that have happened involves a physical process with a definite physical outcome which is then stable over some length of time.

⁵See the Wikipedia entry on *Radiocarbon dating* for a useful discussion.

6.3.1 Recording

Some physical property is set at a specific value by a local physical process, and then stays at the value because a threshold has to be surmounted to reset it.

The kinds of properties that serve as the physical substrate at the lower levels include:

- ***Magnetic states of a magnetizable medium.*** This includes music tape recorders, video tape recorders, and computer secondary memory such as tape drives, hard disks, and erasable optical media ([94]:49-52,54). It is based in the magnetization properties of specific materials ([38]:36-1 to 37-5).
- ***Coded surface properties of a medium:*** Binary data is stored in pits on the surface of CD ROMs ([94]:52-54)). It is based in the stability of material properties (the static properties of solids: [107]:119-145). One can also include in this category, writing and printing on paper.
- ***Electric circuit states:*** Binary data is stored in high/low voltages in specific circuit elements in some memory array, for example clocked D-latches in Static RAM, and capacitors which can be charged or discharged allowing a bit to be stored in Dynamic RAM ([94]:101-111,167-169; [16]:144-148). This is based in the stability of electronic circuit states ([56]:544-554) in the first case, and in active refreshing processes in the second ([94]:110-111). It is also occurs in EEPROMS, where memory states are encoded in electron states in a floating gate in an EEPROM cell ([16]:148-152). A NOR flash cell relies on hot electron injection for programming and quantum mechanical tunneling for erasure, whereas in NAND flash cells both are done by Fowler-Nordheim tunneling.⁶
- ***Biomolecule structure:*** the coding patterns in DNA molecules is a record of evolutionary history, and can be used for dating and cladistic analysis ([103]:21,51-52). This is based in the reliability of the DNA copying process ([11]:293-308).
- ***Pattern of connectivity and activation in network connections:*** The specific pattern of connections and their relative strengths in artificial neural networks and brains records short term and long term memories. In the case of animals and humans ([59]:1227-1246; [11]:1035-1037) it is based in chemical changes and changes in synaptic connections ([59]:1254) involving specific pathways for long terms storage ([59]:1254-1259) and short term storage ([59]:1248-1254). Learning causes a change in cell function by changing synaptic transmission [81]: 363-364). Short term data can also be stored in as activation patterns such as synchronised synchronized activity in brain circuits ([9]:136-174).

Generically, recording takes place through emergence of any identifiable structure that is stable over a relevant time scale.

⁶See the Wikipedia articles on ‘Hot carrier injection’ and ‘Field electron emission’ for discussion and references.

6.3.2 Remembering

is some process whereby the stored record is interrogated: examples are DNA epigenetic processes, reading of memory in computer systems, and recalling memories in one's mind. This is as opposed to interrogating a record, where the record is analyzed rather than being read, as in the cases of geology and archaeology. For memory to be useful, there has to be some kind of indexing system of what is stored: it is no good storing information, if you don't know where it is.

6.3.3 Indexing

The process of indexing needs a sorting and classification system, which will generally involve a modular hierarchical structure used in the classification of folders and files and in assigning names or other identifiers to them as well as to stored entities. In a computer it is implemented at the lower level by association of names with specific memory addresses ([94]:40-44). The index is itself a further form of memory. The computer indexing system is a physically bodied implementation of the user's view of the world. Virtual memory is based on separating address space and memory addresses ([94]:321-362). A memory map relates virtual addresses to physical addresses ([94]:323): a beautiful example of the interaction between the abstract and the physical in a digital computer. DNA coding sequences are another example: epigenetic processes in effect work by using an indexing system for genes when specific genes are turned on and off in response to developmental needs through RNA polymerase binding to a DNA promotor sequence ([11]:315-316).

6.3.4 Deleting

Because of the finite capacity of memory and the ongoing influx of new information, generically one needs some kind of reset process that wipes out old memory to create space for new information to be stored. This is state preparation for the next round of remembering. It will be a non-unitary process, indeed it is precisely here that irreversibility occurs and entropy is generated, as shown by Landauer and Bennett.

However you don't delete all that is in memory: *selective deletion* takes place, because one selects what is deleted and what is kept by deleting unwanted files, emails, and so on. this is therefore a form of adaptive selection: the creating of useful information deleting that which is not useful in relation to some classification system and guiding purpose. What is kept is determined by the user's purpose: this is top-down causation from the user's purpose to the electrons in the computer memory system.

6.3.5 State vector reduction

The crucial feature of all of this in relation to quantum physics is that *every recording event, reading event, and deletion event involves collapse of the wavefunction*. Quantum uncertainty makes way to classical definiteness as each such event takes place. This is happening all the time everywhere as passive records are laid down, as well as when memories are recorded, read, and deleted.

6.4 The ascent of time: emergent properties

The proposal now is that the passage of time, which happens in events such as those just discussed, ripples up from the lower levels to the higher levels through developmental processes that depend on the lower level arrow of time and therefore embody them in higher level processes.

The basic ways the lower level processes embody the arrow of time has been discussed above: they include,

- Things naturally fall downhill,
- Electric currents flow from positive to negative potentials,
- Waves convey information as they spread out from their sources,
- Energy changes from useful to useless forms as dissipative processes take place,
- Diffusion spreads heat and matter out from their sources.

These effects at the basic physics level then affect processes in applied physics, chemistry, all forms of engineering, geology, planetary science, and astronomy, as well as in microbiology, physiology, developmental processes, psychological processes, and evolutionary history, leading to similar effects due to the flow of time. Indeed *it is because this happens reliably that we have our basic concepts of cause and effect*, the latter always occurring after the former. The whole idea of causation is premised on this property.

6.4.1 Local physics and technology

Physicists, chemists, and engineers can assume the 2nd law of thermodynamics holds on macro scales with the forward direction of time. This becomes a basic feature of their analyses [40], involving viscosity, the production of heat, dissipation, and entropy production. It affects entities such as engines, refrigerators, heat exchangers, as well as chemical reactors. Particularly important is the way separation and purification processes underlie our technological capabilities by enabling us to obtain specific chemical elements and compounds as needed - another case of adaptive selection (Section 2.3.4), locally going against the grain of the Second Law at the expense of the environment. The specific processes that enable these non-unitary effects are detailed in [52].

Molecular and solid state systems inherit the arrow of time from their constituents (current flows, rectifiers, gates), leading to electrical and electronic systems [56], computers [94], and nanotechnology devices [107]. The flow of time in the response of the components at each level is used by the designers in making time-responsive higher circuit elements; they are all classical elements, so at their operation emerges out of state-vector reduction at the micro level.

6.4.2 Geological and astrophysical arrow of time

Diffusion plays a crucial role in the environment, where it relates to pollution hazards in the ocean, atmosphere, rivers, and lakes [17].

It occurs in astrophysics, where the Fokker-Planck equation implies continuous production of entropy ([88]: Chapter 4). One-way processes based in the underlying radiative processes and diffusion are important in stars, galaxies, radio sources, qsos, and so on [80, 92]. In particular supernovae are irreversible processes: gravity creates order (attractor of dynamic system: direction comes from initial conditions, SN explosion creates disordered state irreversibly. This is crucial to the formation of planets round second generation stars that can become homes for life ([93]: 345-350).

6.4.3 Biological arrow of time

Biology takes the arrow of time in lower level processes for granted. These time asymmetric processes, e.g. cell processes, synaptic process, propagate their arrow of time up the hierarchy [11] to the macro states. Thus diffusion across synaptic cleft, propagation of action potential from dendrite to axons, the rectifying action of voltage-activated channels underlying the nerve impulse, lead to time asymmetric brain processes. Micro asymmetry in these processes results in emergent time asymmetry in macro events in the brain: emergent structures in biology inherit their arrow of time from the underlying modules and their non-equilibrium interactions.

At the community level, crop ecology depends on the one-way process of leaf photosynthesis ([65]:257-288) and its consequences for plant growth. Dissipative forces in the interaction of components must be modelled in looking at energy flows in ecosystems [70] and in physical processes such as weathering, erosion, and deposition ([100]:225-249,274-280). A thermodynamically based arrow of time is involved, starting at the level of grains of sand and dust particles, and cascading up to weathering of mountains and global spread of pollution.

As for evolution, there is a time asymmetry in the Darwinian evolutionary process: initial conditions on earth were very simple in biological terms, so there was no way but up! At a macro level, fitness flux characterizes the process of natural selection [69] and satisfies a theorem that shows existence of a fitness flux even in a non-equilibrium stationary state. As always, adaptive selection is a non-unitary process. In such processes, energy rate density serves as a plausible measure of complexity [14, 15], but the process is not necessarily always up: evolution is an imperfect ratchet.

6.4.4 Experience and Memory

The process of experiencing and remembering is based in underlying time-asymmetric synaptic processes [59] that lead to the experience of subjective time [45]. It is not clear what role state vector collapse plays here, but presumably having a thought corresponds to state vector collapse, as it is a definite classical outcome at a specific time of underlying quantum processes. What is stored in attention and memory is the outcome

of a non-unitary process of adaptive selection resulting from deletion of unwanted records.

Overall, lower level entities experience an arrow of time because of their context; as they act together to create higher level entities, they inevitably export this arrow of time into the higher level structures that emerge.

7 The nature of spacetime

The passage of time is crucial to the understanding of physical reality presented here: not just as a subjective phenomenon related to the mind, but as an objective phenomenon related to physical processes occurring from the very early universe to the present day. The best spacetime model for what occurs is an evolving block universe (Section 7.1), increasing with time from the start of time until the end of time. This provides the ultimate source of the microphysics arrow of time (section 7.2), as well as a solid reason for preserving causality by preventing existence of closed timelike lines (Section 7.3). It is useful to distinguish between active and passive quantum measurement processes (Section 7.4), the former being associated with specific observational procedures, and the latter with the ongoing process of ordinary events.

7.1 The Evolving Block Universe

The passage of time is a real physical processes, as exemplified in all the cases discussed above. Our spacetime picture should adequately reflect this fact.

The nature of existence is different in the past and in the future - Becoming has meaning ([21]:94-110). Different ontologies apply in the past and future, as well as different epistemologies.

One can express this essential feature by viewing spacetime as an *Evolving Block Universe* (EBU) [95, 27]. In such a view the present is different from the past and the future; this is represented by an emergent spacetime which grows with time, the present separating the past (which exists) from the future, which does not yet exist and so does not have the same ontological status. The past is the set of events that have happened and so are determined and definite; the future is a set of possibilities that have not yet happened. The present separates them, and the passage of time is the continual progression by which the indeterminate becomes determinate.

It must be emphasized here that it is not just the contents of spacetime that are determined as time evolves; the spacetime structure itself also is only definite once events have taken place. For example quantum fluctuations determined the spacetime inhomogeneities at the end of inflation [27]; hence they were intrinsically unpredictable; the outcome was only determined as it happened. The part of spacetime that *exists* at any instant is the past part of spacetime, which continually grows. This is the evolving block universe. The future is a possibility space, waiting to be realised. It does not yet exist, although it is not generic: there are a restricted set of possibilities that can emerge from any specific present day state. Classically they would be determined, but irreducible

quantum uncertainty prevents unique predictions (Section 2.1; [29]). This is where the essential difference between the future and the past arises. Thus in Figure 3, the time up to the present has happened, and everything to the past of the present is determined. The time to the future of the present has yet to occur; what will happen there is not yet determined (unless the viewpoint on indeterminism imbedded at the core of present day present day quantum theory is wrong). The present time is a unique aspect of spacetime at each instant, and it keeps moving up as time elapses.

At a micro level, time passes as wave function collapse takes place, as discussed above: the indefinite future changes to the determined past as this happens. This is possibly best represented as a *Crystalizing Block Universe* (CBU) when we take quantum effects such as entanglement in time into account [33]. When one coarse grains the local micro time determined in this way, related to physical processes by (3), it will lead to the macro time parameter.

7.1.1 The preferred world lines

The past/future cut continually changes with time, at any specific time defining the present, so it is fundamental to physical processes; how is it determined? Physical processes are based in worldlines rather than spacelike surfaces, so this process of becoming determinate happens along preferred timelike worldlines in spacetime, as a function of proper times along those world lines since the beginning of the universe. The metric function determines proper time along each world line as a line integral along timelike world lines - this is a basic feature of general relativity [54] - and so provides the proper time parameter τ at each event that determines the rate at which physical processes happen through local dynamical equations such as the Schrödinger equation (3) at the micro level, and the Maxwell equations and Einstein field equations in the 1+3 covariant form [31] at the macro level .

Because the collapse of the wave function is associated with specific local physical entities [29], these world lines will be fixed by the local motion of matter (for example, a detection apparatus). Hence they will be determined by the timelike eigenvectors of the total matter stress tensor T_{ab} representing the average motion of matter at each event determined on a suitable averaging scale. Through the Einstein equations [54], these will be the timelike eigenvectors of the Ricci tensor R_{ab} , which will be uniquely defined in any realistic spacetime (the real universe is not a de Sitter or Anti de Sitter spacetime).⁷

This process non-locally defines unique surfaces of transition where these transition events are taking place at any specific time, but these surfaces are derivative rather than fundamental: as indicated, the essential physical processes take place along timelike world lines. These surfaces of transition need not be instantaneous for the preferred world lines, and are not even necessarily spacelike. Their existence breaks both Lorentz invariance

⁷There are no preferred worldlines or space sections in special relativity, so the idea does not work in that context; this has been used as an argument against the EBU idea. But general relativity determines the spacetime in the real universe via the Einstein Field Equations, so this indeterminacy is not the physically relevant case and the argument does not apply.

and general covariance; that is fine, this is an unsurprising case of a broken symmetry, as occurs in any specific realistic solution of the field equations (for example any perturbed Friedmann-Lemaître spacetime [19, 31]). The existence of objects (‘reality’) is related to conservation relations between entities at successive times, entailing continuity of existence between correlated sets of properties.

7.1.2 Proposal

In summary,

- **Viewpoint: The evolving nature of space time:** the proposal is a *Evolving Block Universe* picture of spacetime, where the essential difference between the past (it exists) and future (it does not yet exist) generates a time asymmetry in all local physical processes. Spacetime starts at the beginning of the universe and then grows steadily until the end of time. At any instant the ontological nature of the past, present and future is fundamentally different.

The way this asymmetry “reaches down” to the quantum measurement process and the state preparation process is still to be clarified.

7.1.3 The contrary view

This view is of course contrary to that expressed by some philosophers (e.g. [76]) and by many quantum physicists, particularly related to the idea of the wave function of the universe and the Wheeler-de Witt equation (e.g. Barbour [7]). In [29], I claimed that the basis for believing in that approach is not on a solid footing. In brief, the argument is, *We have no evidence that the universe as a whole behaves as a Hamiltonian system.* Indeed, because the behaviour of the universe as a whole emerges from the conjunction in complex configurations of the behaviour of its components, it is likely that this is not true, except perhaps at the very earliest times before complex configurations existed. This argument is made in depth in In [29].

This counter viewpoint is put succinctly by Sean Carroll in a blog:⁸

“The past and future are equally real. This isn’t completely accepted, but it should be. Intuitively we think that the ‘now’ is real, while the past is fixed and in the books, and the future hasn’t yet occurred. But physics teaches us something remarkable: every event in the past and future is implicit in the current moment. This is hard to see in our everyday lives, since we’re nowhere close to knowing everything about the universe at any moment, nor will we ever be - but the equations don’t lie. As Einstein put it, ‘It appears therefore more natural to think of physical reality as a four dimensional existence, instead of, as hitherto, the evolution of a three dimensional existence.’ ”

⁸<http://blogs.discovermagazine.com/cosmicvariance/2011/09/01/ten-things-everyone-should-know-about-time/>

But the question is which equations, and when are they applicable? As emphasized so well by Eddington [21]:246-260), our mathematical equations representing the behaviour of macro objects are highly abstracted version of reality, leaving almost all the complexities out. The case made in [29] is that when true complexity is taken into account, the unitary equations leading to the view that time is an illusion are generically not applicable except to isolated micro components of the whole. The viewpoint expressed by Carroll supposes a determinism of the future that is not realised in practice: *inter alia*, he is denying the applicability of quantum uncertainty to the real universe. But that uncertainty is a well-established fact [39, 46], which can have macroscopic consequences in the macro world, as is demonstrated by the historic process of structure formation resulting from quantum fluctuations during the inflationary era [19]. These inhomogeneities were not determined until the relevant quantum fluctuations had occurred, and then become crystalized in classical fluctuations; and they were unpredictable, even in principle.

7.2 The Arrow of Time

The idea **AT1** (different conditions in the far future and the far past) does not apply, because that cannot be applied if the future does not yet exist. It is rather the combination of **AT2** (setting the master arrow of time) followed by **AT3**, starting at the LSS and then propagating down to lower levels (setting environmental contexts at each level), but then propagating up in emergent structures (effective laws at each level).

Together these create the EBU where the arrow of time is built in to the fact that the past has taken place, and the future is yet to come; the past exists as what has happened, the future as (restricted) potentialities.

- Only radiation from the past can affect us now, as only the past has happened. Radiative energy arrives here and now from the past null cone, not the future null cone (Figure 3).
- Only the retarded Feynman Green's function makes physical sense, because only the past can send causal influences to us. This solves the issue of the local electromagnetic arrow of time.
- The matter that exists here and now was created by nucleosynthesis in the past (Figure 4). It bears in its very existence a record of the events of cosmological and stellar nucleosynthesis. Future potentialities are unable to influence us in this way.
- We can influence the future by changing conditions as to what will happen then; we cannot do so for the past, as it has already occurred. The relevant wave function has already collapsed and delivered a specific result.
- Overall, the micro laws of physics are time symmetric, for example Feynman diagrams can work in both directions in time, but the context in which they operate (the EBU) is not. Thus their outcome of necessity has a determinate arrow of time, which underlies the very concept of causation as we know it. If this was not so, cause and effect would not be distinguishable.

AT3 is needed for time to flow, but does not by itself set an arrow of time (time can flow either way from an initially special set of conditions). That comes from **AT2**. The EBU starts at the beginning of time, embodying the cosmological arrow of time. The future direction of time is that direction in which spacetime is growing. In summary,

The Arrow of Time: On the view presented here, the ultimate resolution of the Arrow of Time issue is provided by the fact we live in an evolving block universe, where only the past can influence us, because the future does not yet exist, so it cannot causally affect us.

7.3 Closed timelike lines

A longstanding problem for general relativity theory is that closed timelike lines can occur in exact solutions of the Einstein Field Equations with reasonable matter content, as shown famously in the static rotating Gödel solution [54]. This opens up the possibility of many paradoxes, such as killing your own grandparents before you were born and so creating causally untenable situations.

It has been hypothesized that a *Chronology Protection Conjecture* [53] would prevent this happening. Various arguments have been given in its support [97], but this remains an *ad hoc* condition added on as an extra requirement on solutions of the field equations, which do not by themselves give the needed protection.

The EBU automatically provides such protection, because creating closed timelike lines in this context requires the determined part of spacetime intruding on regions that have already been fixed. But the evolving spacetime regions can never intrude into the completed past domains and so create closed timelike lines, because to do so would require the fundamental world lines to intersect each other; and that would create a space-time singularity, because they are the timelike eigenvectors of the Ricci tensor, and in the real universe, there is always matter or radiation present. The extension of time cannot be continued beyond such singularities, because they are the boundary of spacetime.

Causality: The existence of closed timelike lines ([12]:93-116) is prevented, because if the fundamental world lines intersect, a spacetime singularity occurs [54]: the worldlines are incomplete in the future, time comes to an end there, and no “Grandfather Paradox” can occur.

7.4 Active and Passive Measurement Processes

A significant implication of the EBU idea for Quantum theory is,

Omnipresence of state vector reduction Collapse of the wave function is not a rare process that only takes place occasionally when an experimenter sets up an experiment. Like decoherence, it takes place all the time everywhere as interactions take place and the indefinite becomes the definite. Many examples above have indicated this happening.

Observers are irrelevant to this process. Physical events were taking place in the very early universe when hydrogen was burning to helium, long before any observer existed. The alternative outcomes for hydrogen and helium interactions at that time did not continue to exist as entangled states. Specific classical outcomes occurred; and they continue to occur, as physical processes unfold.

State vector reduction can be made to take place in specific laboratory situations by careful experimental design, but that is the exception, and is not needed for wave function collapse to take place. At later times omnipresent Cosmic Microwave Blackbody Radiation photons travel on classical paths throughout the universe since decoupling of matter and radiation; they form an effective radiation fluid determining a unique local rest frame everywhere, and causing decoherence everywhere. They travel on classical paths and form a classical fluid.

On this view, “Observation” should be replaced by “Transition to Definiteness” (TTD) or similar, so as to demote the idea of an observer from the process. We need to distinguish,

- **Active measurement process:** interaction between entities (an electron and a photon for example) leads to state vector collapse and hence physical outcomes that result in specific changes in a measuring apparatus such as a CCD, a particle detector, or an animal eye, that result in a macro response being recorded through a specific change in a macro entity; see the examples in Section ???. A signal is recorded that the event happened.
- **Passive measurement process:** interaction between entities (an electron and a photon, or particles in a gas, for example) leads to state vector collapse and hence physical outcomes that result in changes the physical state at the macro level (a gas approaches equilibrium, for example [42]), but this change is not recorded in any macro apparatus. No signal is recorded that the event happened.

It is possible it takes place through a specific local collapse mechanism like the GRW process, but arising due to top-down causation due to the measuring apparatus in the local physical context [29]).

8 The top-down and bottom up cascades

The overall picture that emerges is shown in Diagram 2.

<i>The Arrow of Time</i>		
Cosmology		Brain, Society
<i>Top-down effects</i> ↓		↑ <i>Bottom-up effects</i>
Non-equilibrium environment	⇒	Molecular processes
<i>Top-down effects</i> ↓		↑ <i>Bottom-up effects</i>
Quantum Theory	⇒	Quantum Theory

Diagram 2: *Contextual determination of the arrow of time cascades down from cosmology to the underlying micro processes, on the natural sciences side, and then up to the brain and society, on the human sciences side.*

In summary:

- Spacetime is an evolving block universe, which grows as time evolves. This fundamental arrow of time was set at the start of the universe.
- The observable part of the universe started off in a special state which allowed structure formation to take place and entropy to grow.
- The arrow of time cascades down from cosmology to the quantum level (top down effects) and then cascades up in biological systems (emergence effects), overall enabled by the expanding universe context leading to a dark night sky allowing local non-equilibrium processes to occur.
- There are an array of technological and biological mechanisms that can detect the direction of time, measure time at various levels of precision, and record the passage of time in physically embodied memories.
- These are irreversible processes that occur at the classical level, even when they have a quantum origin such as a tunneling process, and so at a foundational level must be based in the time-irreversible quantum measurement process.
- In conceptual terms they are the way the arrow of time parameter t in the basic equations of physics (the Dirac and Schrödinger equations (3), Maxwell's equations and Einstein's equations on the 1+3 covariant formulation [31]) is realised and determines the rate of physical processes and hence the way time emerges in relation to physical objects.
- Each of these processes is enabled by top-down action taking place in suitable emergent local structural contexts, provided by molecular or solid-state structures. These effects could not occur in a purely bottom-up way.

8.1 A contextual view of the arrow of time

This paper has extended the broad framework of [29] to look in detail at the issue of the arrow of time. It has made the case that this is best looked at in terms of the hierarchy of complexity (Table 1), where both bottom-up and top-down causation occur. Detailed examples have been given of how this works out in terms of arrow of time detectors, clocks, and records of past events.

Key to this is the time-asymmetry of the quantum measurement process, which I suggest emerges in a contextual way. Firstly, a detection process depends on setting the detector into a ground state before detection takes place (analogously to the way computer memories have to be notionally cleared before a calculation can begin). This is an asymmetric adaptive selection process, because what is needed is kept and what is not

needed is discarded, whereby any possible initial state of the detector is reduced to a starting state, thereby decreasing entropy. It will be implemented as part of the detector design.

Secondly, the asymmetry of the collapse process must presumably rely on the fact that the future does not yet exist in a EBU (Section 7), hence we cannot have advanced Green functions contributing to a Feynman propagator, nor the future contributing to a state vector reduction process. There does not seem to be any other plausible way to relate the global cosmological arrow of time to the local arrow of time involved in collapse of the wave function. How this happens needs to be elucidated, as part of the investigation of how state vector collapse takes place as part of a top-down process in specific physical contexts.

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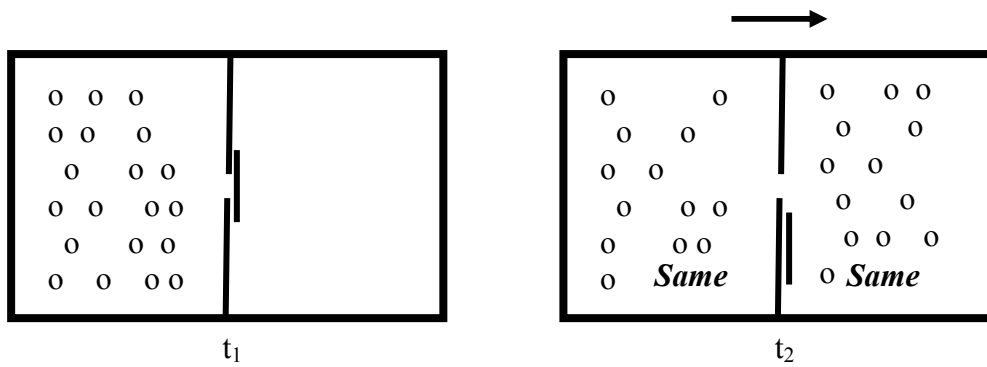


Figure 1a: initial state

Figure 1b: final state

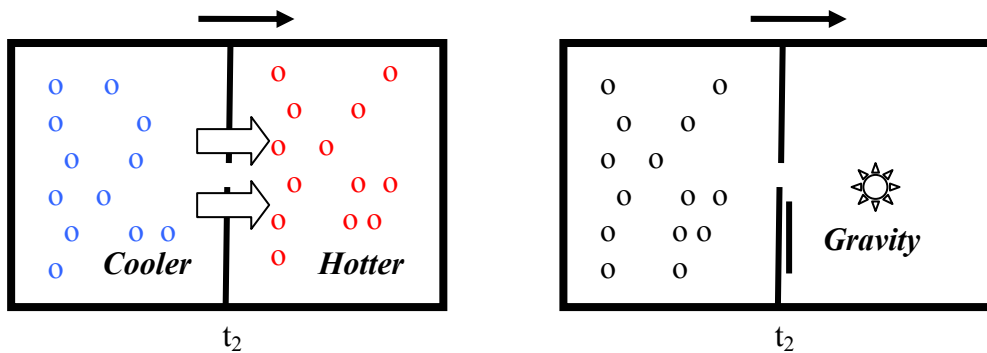


Figure 1c: final state with a gate that only lets through high speed molecules (Maxwell's Demon)

Figure 1d: final state with gravity (mass greater than Jeans mass)

FIGURE 1: THE DIFFUSION ARROW OF TIME

Figure 1a: Two compartments are separated by an opening, but it is closed. Gas is on the left, the right is empty. This is the prepared starting state: it does not occur naturally.

Figure 1b: opening the aperture results in the gas spontaneously spreading to the other half, until equilibrium is reached and entropy is maximised. The arrow of time is evident in this flow, which is enabled by billions of state vector reduction events at the quantum level (because the outcome is a well determined classical state). The transition from the first state to the second state can be used as an arrow of time detector (given photographs of state 1 and state 2, you can reliably time order them). That deduction assumes no human intervention (in fact the improbable initial state was prepared by humans: another non-unitary transformation).

Figure 1c: If a gate only lets through high speed molecules, the second compartment will become hotter than the first, in apparent contradiction with the second law. This is an example of creating order by selection (slower molecules are rejected).

Figure 1d: If gravity is turned on, so that the Jeans mass is attained in the right hand compartment, structure will spontaneously form. This is presumably in accord with the second law of thermodynamics, but we have no definition of gravitational entropy that makes this good.

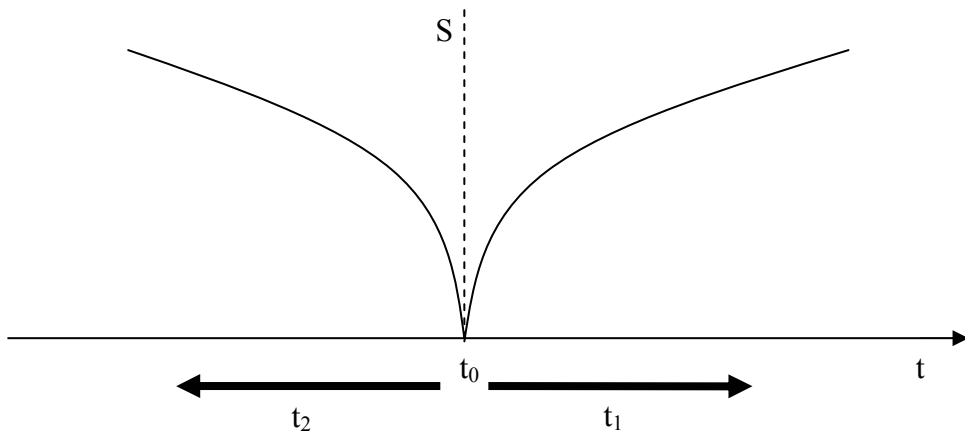


FIGURE 2: THE PAST CONDITION AND THE ARROW OF TIME

The past condition is set at time t_0 : things are smooth there. This enables time to run to the future direction of t , giving time t_1 . Entropy increases (Boltzmann's H-Theorem). But it could equally set off in the opposite direction, giving time t_2 . So we run into Loschmidt's paradox: the H-theorem works in both direction of time. If t_0 is a start event, the past condition (things were special at the start) allows time to flow, but does not determine the direction of time.

But this does not account for the fact that the initial direction of time t was chosen arbitrarily. From a physical viewpoint, whichever direction it goes (t_1 or t_2) will be the direction in which structure formation starts, and so will *by definition* be the forward direction of time from the start event (*vide* matter and antimatter: whichever dominates is by definition "matter"). If they both happened there would be two opposite developments that would each experience themselves as moving forward in time. Hence the past condition sets up conditions whereby time can run; the direction of time then chooses itself as whichever direction things happen.

FIGURE 3 CAPTION: OUR COSMIC CONTEXT

A conformal diagram of the cosmic context for local existence. Time runs vertically, 2 space dimensions horizontally (one space dimension is hidden). Light rays travel at 45° to the vertical. The start of the universe is indicated at the bottom (this might possibly represent a start a finite time ago, or at minus infinity; conformal diagrams do not represent distance or proper time accurately). This is followed by a pre-inflation quantum gravity era, an inflationary era, and a Hot Big Bang (HBB) era, which ends at the surface of last scattering (LSS). The LSS marks the start of structure formation, which extends from the LSS to the present time. Structure formation may continue for some time to the future, but will eventually come to an end. The far future boundary of the universe may lie a finite time to the future, but more probably is an infinite proper time to the future.

The Earth's world line is the vertical line at the centre, with the present time "here and now" marked. Our past light cone extends down to the LSS, which it intersects in a 2-sphere; this is set of events from which the 2.7K cosmic microwave background (CMB) originated. We cannot see to earlier times because the universe was opaque in the HBB era; hence the matter world lines through this 2-sphere form our visual horizon (the surface in spacetime separating matter we can have seen from that which we cannot detect by any electromagnetic radiation).

For all practical purposes, "infinity" for local physics is a sphere of radius 1 light year around the Earth. This is our "Finite Infinity", its world tube surrounding our world-line in spacetime. Our future light cone intersects it in the 2-sphere Fi^+ (our outgoing radiation sphere), and our past light cone intersects it in the 2-sphere Fi^- (our incoming radiation sphere); this is our effective sky -- every star and galaxy we see is an image on this sphere.

On the Block Universe view of spacetime, everything here from the start to the finish exists as a single spacetime block, where all times are equal so the present has no meaning. On the Emerging Block Universe (EBU) view, the present is the special time where, at this instant, the uncertain future is changing to the determined past. Hence on this view, the nature of existence is different in the past (below the surface labeled "The present time") and in the future (above that surface). The former exists (as it has been determined), whereas the latter is presently only potential (so does not yet exist). As time progress, the present time moves up our world line, so the past region of spacetime is continually getting bigger: spacetime is growing. In the far future, when everything has happened, the present will coincide with the future boundary and the EBU will have evolved into a Final Block Universe.

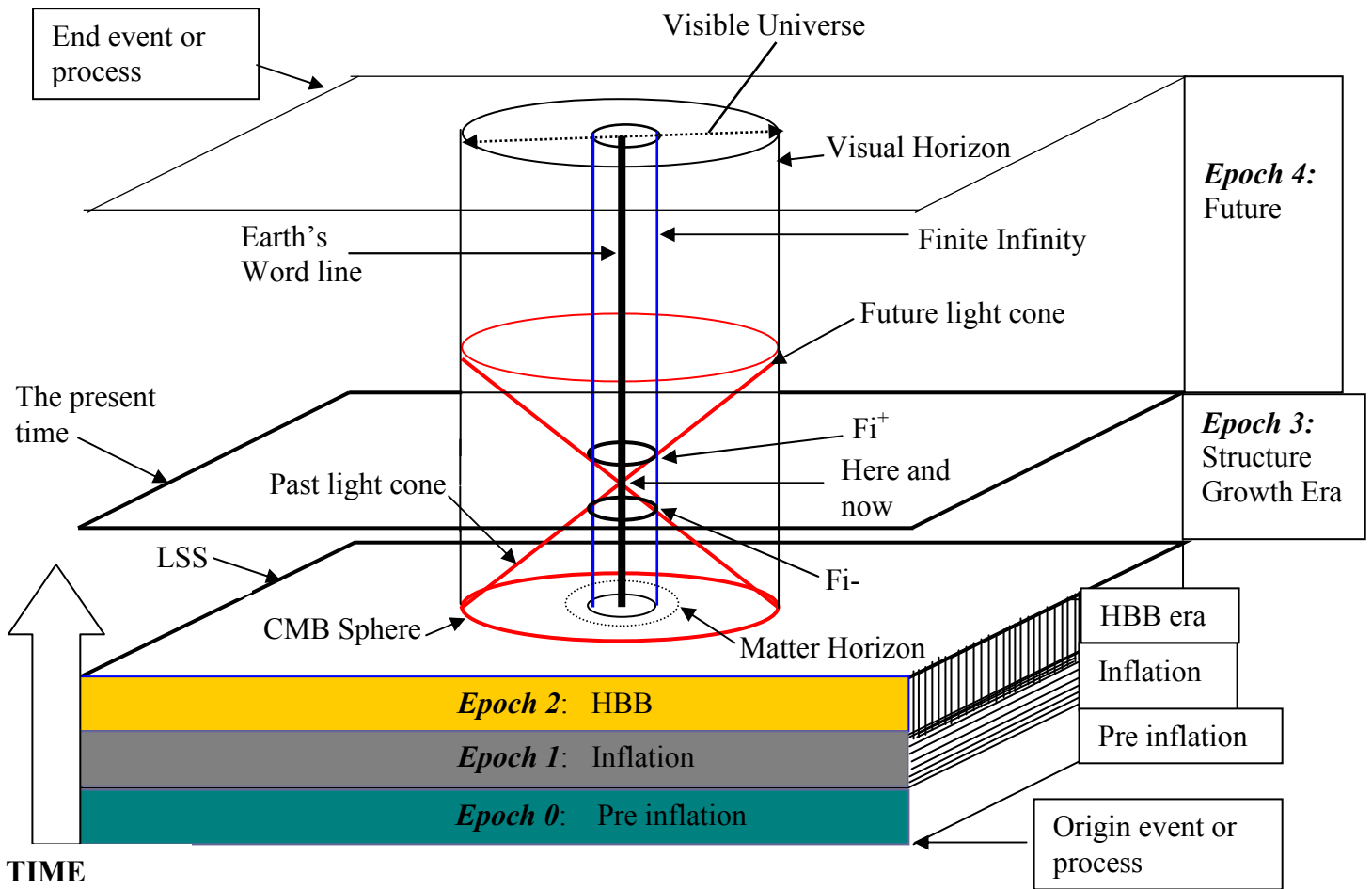
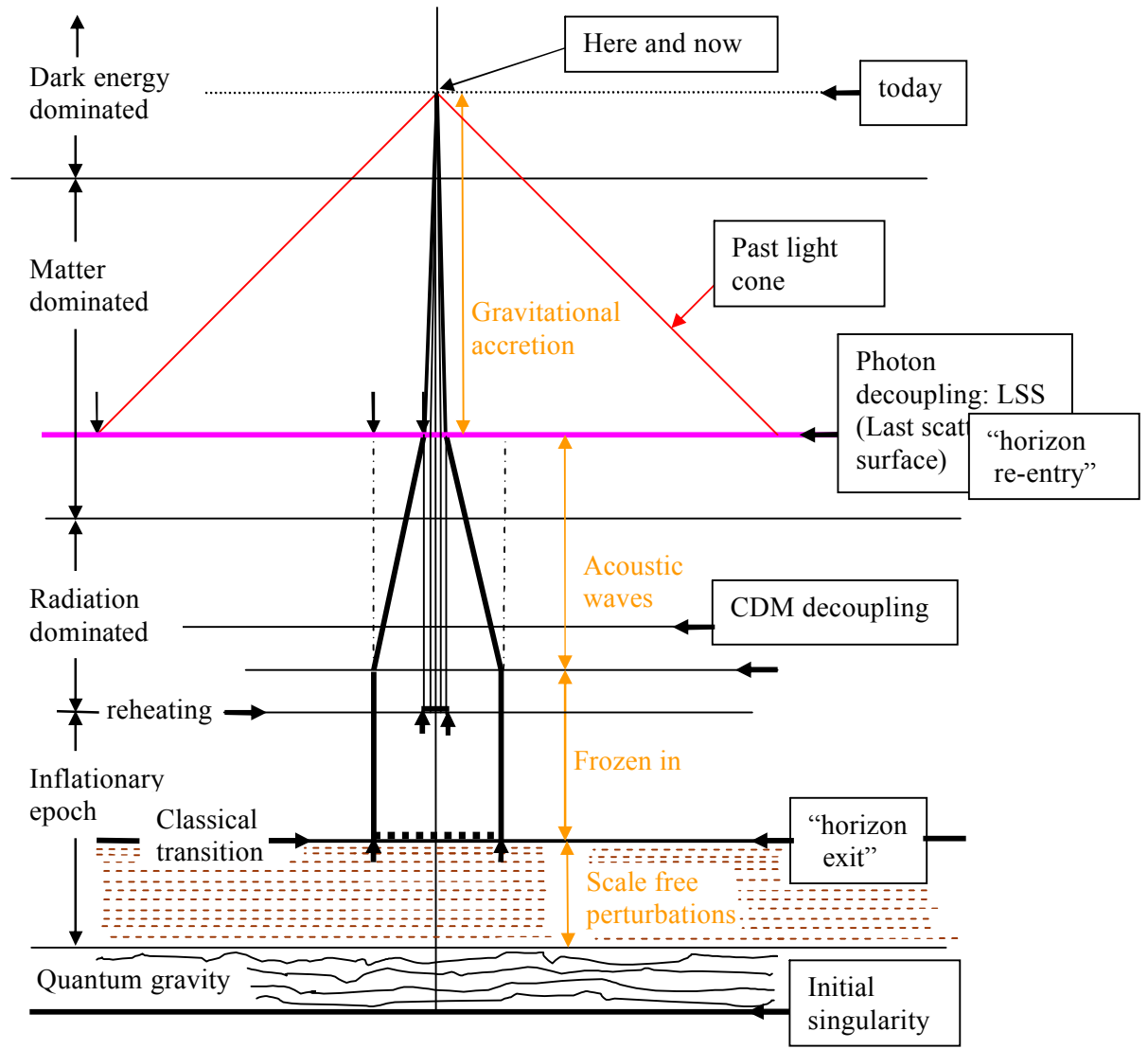


FIGURE 3: Our Cosmic Context



The three downwards pointing arrows on the LSS (photon decoupling) show (left to right) the size of the visual horizon, and the comoving size of the effective domain of influence between the start of the inflationary era to horizon re-entry in the radiation dominated era, and at decoupling of matter and radiation (NB: not to scale!). The two inner upward pointing arrows show the size of the matter horizon at the origin of the MW matter when reheating takes place at the end of inflation.

Figure 4: Effective Domains of influence: Space time diagram.

Caption: The co-moving size of the effective domain of influence (dark broken line stretching down from “here and now”) is slightly increasing as one goes back into the past in the matter dominated era, as matter accretes onto the central mass. It increases as $c/\sqrt{3}$ in the radiation dominated (acoustic oscillation) era until “horizon exiting”, when it becomes constant until horizon exit, which is where the relevant perturbations become classical. The visual horizon size is given by the past light cone intersecting the last scattering surface; the particle horizon size would be attained by extending the past light cone to the start of the quantum gravity era.

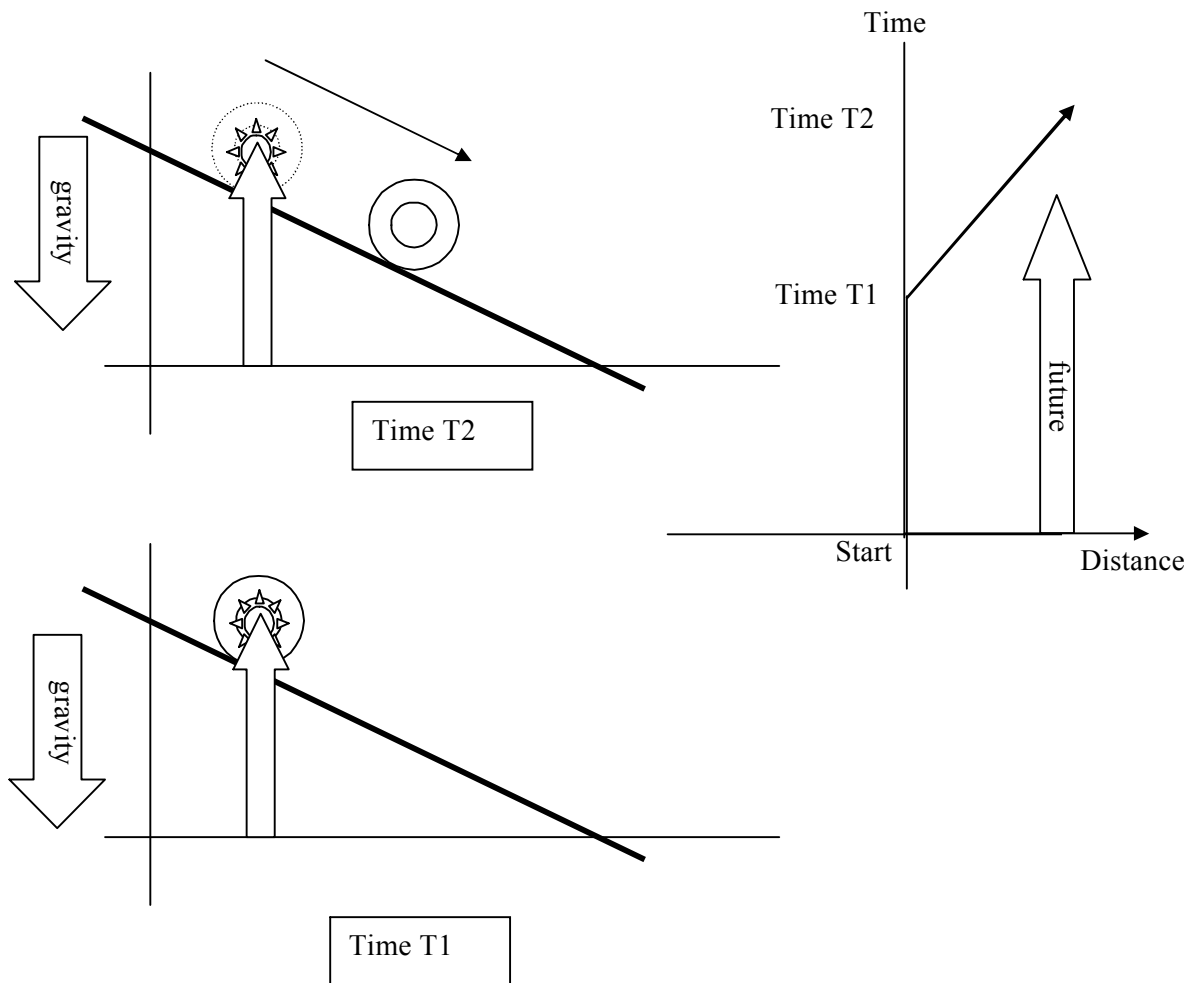


FIGURE 5: An Arrow of Time Detector.

A wheel is clamped in a static state for an extended period on a downhill slope; during that time dynamics does not distinguish an arrow of time (because there is no dynamics!). The slope establishes a spatial asymmetry.

At time T_1 it is released. The time T_2 when it has rolled some distance down the slope is later than time T_1 : the rolling down the slope (to the right) establishes which is the past and which the future direction of time.

If the wheel had not been clamped before the start instant, the motion would have been time symmetric (it could have rolled up to an instantaneous stationary state at time T_1 and then down again) and no arrow of time would have been determined by the dynamics.

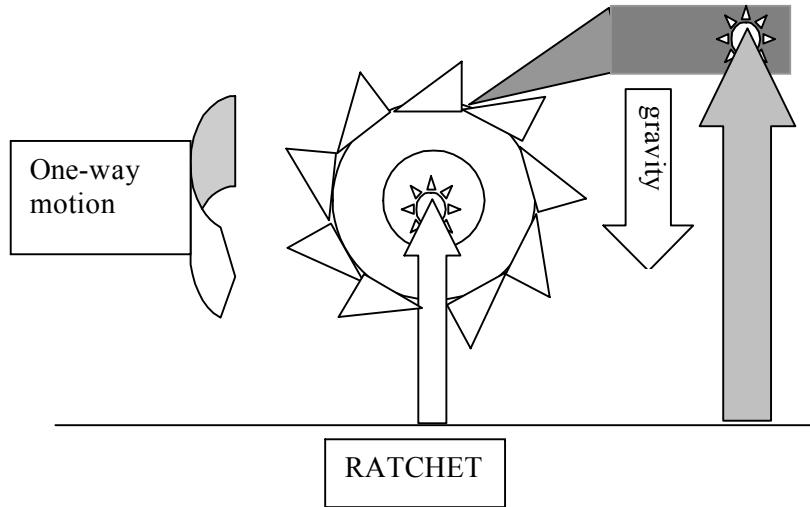


FIGURE 6: An Arrow of Time Detector.

A ratchet wheel is constrained to rotate only one way by a pawl held down by a spring or by gravity. Its one way motion characterizes the future time occurring in the Newtonian equations of motion. Its environment must be cool.