The evolving block universe and the meshing together of times

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It has been proposed that spacetime should be regarded as an evolving block universe, bounded to the future by the present time, which continually extends to the future. This future boundary is defined at each time by measuring proper time along Ricci eigenlines from the start of the universe. A key point, then, is that physical reality can be represented at many different scales: hence, the passage of time may be seen as different at different scales, with quantum gravity determining the evolution of spacetime itself at the Planck scale, but quantum field theory and classical physics determining the evolution of events within spacetime at larger scales. The fundamental issue then arises as to how the effective times at different scales mesh together, leading to the concepts of global and local times.

Keywords: spacetime; arrow of time; block universe; flow of time; chronology protection

Time as an illusion: the block universe

This paper is one of a series of papers developing a proposal for an evolving block universe (EBU) picture of spacetime, instead of the usual proposal of a block universe (BU), summarized later. What is novel in this paper is a new set of answers to criticisms of the EBU proposal, and the development of the way the multiscale structure of physical reality (see Table 1) relates to it.

The basic criticisms of the EBU

Some critics of the EBU picture of spacetime argue against obvious motivations for rejecting the BU proposal, namely that it contradicts both everyday experience and other scientific areas (e.g., nonequilibrium thermodynamics and the second law), noting that defenders of the BU picture like Huw Price argue that it is perfectly consistent with experience and entropy. However, I shall point out later that this claim of consistency can only be sustained by ignoring much evidence at both the macro- and microscale. In particular, this view does not take quantum physics seriously.

Another criticism is that both special relativity (SR) and general relativity (GR), with other usual assumptions, strongly imply a BU, and there are only two approaches to arriving at something other than a BU: (1) add something novel to relativity such as a preferred frame, or (2) reject realism about Minkowski spacetime. My program specifically introduces a preferred frame, and so satisfies the first requirement. Regarding the second point, Einstein's general theory of relativity (GR) is the valid classical theory of gravity and spacetime. The foundation of that well-established theory is that Minkowski spacetime does not describe the real universe; it exists as a Platonic mathematical entity, but not in physical reality. Thus, consistently with GR, I reject physical realism about Minkowski spacetime.

The BU

There is a prevalent view in fundamental physics that space and time are best described as a four-dimensional spacetime that represents all the places and all the times that ever exist as a single unchanging entity. There is no essential difference between the past and the future, because there is no present time defined to separate them; they cannot be distinguished from each other, so there is no meaningful present. Without an objective present, time does not flow in any real sense: the passage of time is an illusion.
Table 1. Five levels of representation of physical reality, with each higher level emerging from the level below it by coarse graining to the appropriate scale

| Scale 4 | Cosmology |
|---------|-----------|
| Scale 3 | Astrophysical structures |
| Scale 2 | Macrolevel: daily life |
| Scale 1 | Microlevel: quantum physics |
| Scale 0 | Quantum gravity |

The underlying dynamical idea is that, given data at an arbitrary time, everything occurring at any later or earlier time can be uniquely determined from that initial data by time-reversible Hamiltonian dynamics, which is assumed to be the basis of dynamics of physics in general and of gravitation in particular. The future and the past are both uniquely predictable from the present because one can predict the state \( S(x, t) \) equally to the past and the future from data given at an initial time \( t_0 \):

\[
H: S(x, t_0) \rightarrow S(x, t_1) \quad \text{for all } t_1.
\]

However, there is nothing special about \( t_0 \): it is an arbitrary choice. Consequently, nothing can be special about any particular moment; there is no special “now,” which can be called the present.

Such a view can be formalized in the idea of a BU, where space and time are represented as merged into an unchanging spacetime entity, with no particular space sections identified as the present and no evolution of spacetime taking place. The universe just is a fixed four-dimensional spacetime block, representing all events that have happened and that ever will happen. \(^9,10\)

Past, present, and future are equal to each other, for there is no surface that can uniquely be called the present. This implicitly embodies the idea that time is an illusion: time does not “roll on.”

**The problems**

We explicitly or implicitly represent physical reality in terms of different scales of description, with larger scales emergent from smaller scales through coarse graining, \(^4,11\) but also with higher levels influencing lower-level events in many ways. \(^4,11–14\) One can consider a great many levels of description, but for present purposes a five-scale description will suffice, as shown in Table 1.

The issue, then, is on which scales the BU description might be accurate, and how the descriptions at different scales relate to each other. A key point is that spacetime curvature is determined at scale 3, because smaller scale entities have a negligible effect on this curvature. Events within spacetime are determined by the interaction between entities at scales 1 and 2.

**Scale 2: macroproblems**

At the macrolevel, dynamics is almost never time reversible: Hamiltonian development is in flagrant contradiction to our experiences in everyday life, as well as all of biology and biochemistry. This is the profound content of the second law of thermodynamics, a fundamental feature of the macro world of physics, chemistry, and biology. \(^13–17\) Wine glasses fall and break, books get burnt and their ashes get scattered to the wind, and species die out and traces of most of them are lost. Furthermore, chaotic dynamics amplifies microfluctuations to the macroscale. At the macroscale, the reversible dynamics (Eq. (1)) is mostly not valid: conditions in the past do not uniquely determine the future, or vice versa. Examples abound: the classic example is weather forecasting, other examples are where and when lightning will strike, when automobile accidents will happen, and when shares on the stock market will rise. One only knows what will happen when it happens; it is not predictable. Hamiltonian dynamics does not apply. Hence, a BU representation is not appropriate at that scale.

However, the idea then proposed \(^17\) is that, nevertheless, there is indeed reversible Hamiltonian dynamics at the microlevel, but through coarse graining it leads to irreversible physics at the macrolevel, because microinformation is lost through the coarse graining. The second law of thermodynamics arises through special initial conditions, but the dynamics is actually time reversible, it is just that we cannot see this fundamental feature because our senses are too coarse. If we could accurately reverse all the microvelocities, the macrolevel description would run in reverse: the fragments of glass on the floor would reassemble into the intact wine glass; the ashes of the burnt book would come back on the wind and recreate the pristine object. The true picture is time reversible, it is just our coarse macrovision that prevents us seeing this. Even if the BU is not a good description at the macrolevel, it is indeed good at the microlevel, so a BU picture is justified at that level and represents the true situation.
This view is, however, not applicable to cases such as deleting memory files in a digital computer. Once they are overwritten, records are irretrievably lost; no trace is left, information is gone. This is based on the physics of read-and-write operations in a digital computer (see Ref. 18, pp. 431–460), based on the properties of registers (pp. 354–364) because of latch property and the underlying basis in flip-flops (p. 371). In the end, this irrevocable irreversibility, typical of all adaptive selection processes, is based on the properties of the underlying quantum physics.

**Scale 1: microproblems**

It is often stated that, because quantum physics is based on unitary evolution of the wave function, fundamental physics is Hamiltonian and information is never lost. The following quote by Fabbri and Salas,19 made in the context of the debate on the black hole information paradox, is typical:

> The type of radiation emitted does not allow the recovery of the information about the star from which the black hole was created. Therefore, with the disappearance of the black hole this information will be lost forever. But this is forbidden by the basic principles of quantum mechanics itself.

**No collapse.** The authors therefore believe in a version of quantum mechanics (QM) where the nonunitary irreversible process of collapse of the wave function,20–24 when information is indeed lost (see later), never occurs. Thus, in their version, measurements never take place. But the quantum probabilities that the wave function is supposed to represent are never realized in physical reality if no collapse of the wave function ever takes place.

Please consider Figure 1, showing the classic double-slit experiment build-up of an interference pattern of single electrons. Each dot represents an individual particle arrival, and hence represents nonunitary behavior because in each case a specific classical outcome has occurred (see “Quantum dynamics and nonunitary evolution”). Quantum theory very successfully predicts the statistics of the outcome and the interference patterns that build up, but it cannot predict where each individual particle will arrive. These individual outcomes are not predictable, as they are essentially uncaused; they are only determined as they happen.

The claim that QM is unitary is conclusively proved wrong by this experiment. There are, however, four counters to this argument, which I now consider in turn.

**Ensemble.** The first response is that quantum physics is not about individual events, it is about statistics of events. While the quantum calculation cannot predict where each individual particle will arrive, it very successfully predicts the statistics of the outcome and associated energies, scattering angles, and similar measurable properties, without considering the process of wave function collapse. This is all physics needs, so it does not matter that this nonunitary behavior related to individual events occurs. We just need to consider the statistics of the ensemble.

The reply is that there is no ensemble to consider unless the individual events that make up the ensemble occur. Hence, no statistics of outcomes exists without the nonunitary behavior represented by the successive appearance of the individual dots on the screen, each of which represents an event where collapse of the wave function occurs. And it is not always true that only the statistics count: specific collapse events can sometimes have crucial macro-outcomes (see “Quantum dynamics and nonunitary evolution”).

**Decoherence.** The second response is that environmental decoherence,22 which diagonalizes the density matrix, gives effective collapse of the wave function.

The reply is that this is not in fact the case: while decoherence indeed diagonalizes the density matrix and hence gets rid of entanglement, it does not set all the diagonal elements of the density matrix to zero except one, and so it does not get rid of superpositions. Thus, it does not lead to classical outcomes, and so cannot account for the individual events seen in Figure 1.

**Many worlds.** The third is the Everett many-worlds view,22 where unitarity is preserved by denying the occurrence of wave function collapse. Reality is viewed as a many-branched tree, where every possible quantum outcome occurs as superpositions are generated by the unitary dynamics. All possible alternative histories occur, each representing an actual universe.
This proposal raises major philosophical issues relating to testability and to Occam’s razor, and there are significant problems to do with the issue of measures, a preferred basis, and how this approach gives the Born probability rule. However, for present purposes the key point is that the many-worlds proposal does not give the BU—it gives an ever-branching spacetime with billions and billions of ongoing bifurcations (see Ref. 25, Figs. 8.10 and 12.2 for the case of just one such bifurcation). This looks nothing like the standard BU, and the resulting spacetime has never been described in coordinate terms (new coordinates would need to be added every time a bifurcation takes place).

This proposal does not support the BU view: it gives a completely different spacetime picture, which we cannot adequately represent by any spacetime diagram at all. If we could, there would also be an evolving Everett universe version, which would be required to adequately represent the passage of time. I will not consider this proposal further here.

**Hidden variables.** Finally, there may be as-yet undiscovered and unobserved hidden variables underlying the apparent randomness of quantum outcomes. There are many problems arising from such theories (see Ref. 22), which I will not discuss here; from a practical viewpoint, until such time as any such hidden variables are characterized and measured, quantum physics is experienced in practice as a theory with outcomes exhibiting irreducible randomness, as shown in Figure 1.

**Scale 3: the micro–macro connection**

We have seen that real-world evolution of events is not unitary on scales 1 and 2. What about scale 3? It is also not unitary on this scale, because of the current standard model of cosmology, which includes an epoch of inflation—an extraordinarily rapid accelerating expansion for a very brief period—at very early times.²⁶–²⁸

This situation is represented in Figure 2. The key point is that quantum fluctuations in the inflationary epoch generated inhomogeneities on the surface of last scattering of matter and radiation, which then provided the seeds for growth of inhomogeneities by gravitational collapse. This was the
Figure 2. According to the standard inflationary picture, the present-day large-scale structure in the universe is the outcome of quantum fluctuations during inflation. Hence, the specific individual galaxies that occur are not determined by initial data at the start of inflation.

The origin of large-scale structures such as clusters of galaxies at the present time. But because they were quantum fluctuations, complete knowledge of the state of the universe at the start of inflation does not determine what specific fluctuations occurred on the surface of the last scattering, and hence what large-scale structures exist in the universe today. The specific outcomes of these Gaussian random processes were only determined as they occurred. The evolution of matter—and hence of spacetime geometry—at scale 3 has been nonunitary over cosmic timescales because of this extraordinary micro–macro connection caused by the mechanism of inflation. In effect, the uncertainty of individual events shown in Figure 1 occurs writ large in the sky because of the cosmological context depicted in Figure 2.

Conclusion
The BU spacetime model is inadequate on scales 1, 2, and 3. We must be able to do better, adequately representing the fact that, in the real universe, unpredictable things happen at each of these scales as time progresses. In actual fact, physical outcomes do not proceed in a unitary way.

The EBU
In contrast to the usual BU view, one can suggest that the true nature of spacetime is best represented as an EBU, a spacetime that grows and incorporates ever more events, “concretizing” as time evolves along each world line. This is the same as the usual four-dimensional BU except that the future boundary of spacetime no longer represents the infinite future: it represents the present time, which is that instant along our world line where the indefiniteness of the future changes to the definiteness of the past. It continually moves to the future, incorporating ever more spacetime events as time passes.

The basic idea
Consider a massive object with two computer-controlled rocket engines that move it right or left. Let the computer determine the outcome on the basis of measurements of decay products of radioactive atoms. The outcome is unpredictable in principle, because of the foundational quantum uncertainty of the photon-emission process. If the object is massive enough, it curves spacetime, and so the future spacetime structure is not determinable or predictable from current data. Selection of the specific path taken, and hence the spacetime structure that results, occurs on an ongoing basis as radioactive decay takes place in an unpredictable way. The change from uncertainty to certainty takes place at the ever-changing present, where the indefinite future becomes the determined past (Fig. 3).
Figure 3. Spacetime diagram of a massive object driven by computer-controlled rocket motors in an unpredictable way. On the left, the situation at time $t_1$: there are many paths possible. On the right, the situation at time $t_2$: all but one option at time $t_1$ have been rejected, one path has been chosen. A further set of options are open at time $t_2$.

The future does not exist in the same sense as the past or the present.

- The past has been determined and is fixed; it has, in various ways, influenced what occurs today.
- The future is uncertain and still has to be fixed; because of quantum uncertainty, it is not true that the future is determined at the present time.
- The present is where the change takes place. It is crucially different from the past and future, and indeed separates them: it is the future boundary of the determinate spacetime region.

Thus, the EBU (Fig. 4) is exactly the same as the BU, except it has a future boundary, namely the present, which is not static: it continually extends in the future direction of time. Spacetime itself is growing as time passes.\(^1\)\(^-\)\(^4\),\(^29\) This obviously represents the passing of time in a more satisfactory way than the usual BU.

**The problem of the present time**

The primary problem with this proposal is the claimed unique status of “the present” in the EBU—the surface where the indeterminate future is changed to the definite past at any instant. It is a fundamental feature of SR that simultaneity is not uniquely defined: it depends on the state of motion of the observer.\(^16\),\(^23\),\(^30\) Hence, it is claimed that no preferred present time can exist, hence the BU model is the only way a spacetime model can take account of this lack of well-defined surfaces of instantaneity.

**General relativity.** However, it is GR that describes the structure of spacetime, not SR. Gravity governs spacetime curvature; the metric tensor is determined by the matter present through the Einstein field gravitational equations.\(^31\) Because there is no perfect vacuum anywhere in the real universe, *inter alia* because cosmic black-body background radiation\(^26\)-\(^28\) permeates the solar system and all of interstellar and intergalactic space, spacetime is nowhere flat or even of constant curvature; therefore, there are preferred time-like lines everywhere in any realistic spacetime model. The SR argument does not apply: Minkowski spacetime does not exist in physical reality.

**The irrelevance of simultaneity.** Furthermore, simultaneity as usually defined, determined by radar,\(^30\) is irrelevant to physical causation. Consider the Mars Rover, controlled from Earth. There is a communication time delay between Earth and Mars that is about 20 min on average. What matters physically is $E_1$ (emission of a control signal from Earth), $E_2$ (reception at Mars and emission of reply), and $E_4$ (reception of this reply back at Earth). Which event $S$ is simultaneous with $E_2$ has no physical significance: it only has psychological value.
Evolving block universe

Figure 4. The evolving block universe: a spacetime that is at each instant bounded to the future by the ever-changing present time. As time passes, the future boundary of spacetime extends to include more events; the initial boundary (the start of the universe) is fixed and unchanging. This extension takes place along preferred time-like world lines.

Resolution. Physically, things happen along time-like world lines rather than on space-like surfaces. What matters physically is proper time measured along preferred timelines $x^i(v)$ by perfect clocks, determined in terms of the metric tensor $g_{ij}(x^k)$ by the basic formula $^{30,31}$:

$$\tau = \int (-ds^2)^{1/2} = \int (-g_{ij}(dx^i/dv)(dx^j/dv))^{1/2} dv.$$  \hspace{1cm} (2)

Time of determination. Starting at the beginning of time, measuring proper time $\tau$ given by Equation (2) along fundamental world lines determines the present instant at time $\tau$ as time passes on each of these preferred fundamental world lines. This happens locally everywhere, determining the present time $\tau$ along each such world line, for each value of $\tau$.

Resultant surfaces of change. Natural surfaces of constant time are given by this integral since the start of the universe. Thus, we can propose that fundamental world lines exist: $^3$ the proper time integral (Eq. (2)) used to define the present is taken along the world lines with four-velocity $u^a(v)$ satisfying Equation (3). This defines unique surfaces $S(\tau)$ in spacetime for each value of $\tau$ up to the present value $\tau_0$.

This procedure is well defined in any realistic cosmological model, and will give the usual surfaces of constant time in the standard Friedmann–Lemaître–Robertson–Walker (FLRW) cosmologies.

What about simultaneity?. In general, these surfaces are not related to simultaneity as determined by radar; indeed, this is even so in the FLRW spacetimes (where the surfaces of homogeneity are generically not simultaneous according to the radar definition$^{33}$).

The preferred world lines. A unique geometrically determined choice for fundamental world lines is the set of time-like eigenlines $x^i(v)$ of the Ricci tensor on a suitable averaging scale, representing the local average motion of matter$^{27,32}$ (they will exist and be unique for all realistic matter, because of the nonzero cosmic background radiation and the energy conditions$^{31}$ such matter obeys). Their four-velocities $u^a(v) = dx^a(v)/dv$ satisfy

$$T_{ab}u^b = \lambda_1 u^a \Leftrightarrow R_{ab}u^b = \lambda_2 u^a,$$ \hspace{1cm} (3)

where the equivalence follows from the Einstein field equations. Thus, we can further propose that fundamental world lines exist: $^3$ the proper time integral (Eq. (2)) used to define the present is taken along the world lines with four-velocity $u^a(v)$ satisfying Equation (3). This defines unique surfaces $S(\tau)$ in spacetime for each value of $\tau$ up to the present value $\tau_0$.
surfaces determined in this way are not even necessarily space-like in an inhomogeneous spacetime. In that case, the implied initial value problem will locally be time-like, and the way it works will need to be rethought.

The evolution of spacetime

The metric evolution. If the metric tensor determines proper time, what determines the metric tensor? The Einstein field equations, of course! Following the ADM formulation, the first fundamental form (the metric) is represented as

$$ds^2 = \left( -N^2 + N_i N^i \right) dt^2 + N_i dx^i dt + g_{ij} dx^i dx^j,$$

where $i, j = 1, 2, 3$. The lapse function $N(x)$ and shift vector $N^i(x)$ represent coordinate choices, and can be chosen arbitrarily; $g_{ij}(x)$ is the metric of the three spaces $\{ t = \text{const} \}$. The second fundamental form is $\pi_{ij} = n_{ij}$, where the normal to the surfaces $\{ t = \text{const} \}$ is $n^i = \delta^i_0$. The matter flow lines have tangent vector $u^i = \delta^i_0$ (which differs from $n^i = g^{ij} n_j$ whenever $N^i \neq 0$). The shift vector $N^i(x^j)$ gives the change of the matter lines relative to the normal to the chosen time surfaces. The lapse function $N(x^j)$ gives the relation between coordinate time and proper time along the normal lines.

The field equations for $g_{ij}(x^k)$ are as follows (where three-dimensional quantities have the prefix (3)): four constraint equations

$$^{(3)} R + \pi^2 - \pi_{ij} \pi^{ij} = 16\pi \rho_H,$$

$$R^\mu := -2\pi^\mu_j = 16\pi T^\mu_0,$$

where “$j$” represents the covariant derivative in the three surfaces, and 12 evolution equations

$$\partial_t g_{ij} = 2Ng^{-1/2}(\pi_{ij} - 1/2g_{ij} \pi) + N_{ij} + N_{ji},$$

$$\partial_t \pi_{ij} = -Ng^{-1/2}(^{(3)}R_{ij} - 1/2g_{ij} R) + 1/2Ng^{-1/2}g_{ij}(\pi_{mm} \pi^{mm} - 1/2\pi^2) - 2Ng^{-1/2}(\pi_{im} \pi^m_j - 1/2\pi \pi_{ij}) + \sqrt{g}(N_{ij} - g_{ij} N^m_{|m}) + (\pi_{ij} N^m)_{|m} - N_{ij|m} \pi^m_j - N_{j|m} \pi^m_i + 16\pi^{(3)} T_{ij}.$$

What determines how the matter evolves? The matter–energy–momentum conservation equations

$$T^\alpha_{\;\beta} = 0$$

must be satisfied. Their outcome is deterministic when equations of state for the matter terms $\rho_{ij}$, $T^\mu_0$, and $^{(3)}T_{ij}$ in Equations (5), (6), and (8) are added, perhaps depending on internal variables such as temperature ($T$), entropy ($S$), or enthalpy ($H$). These relations specify the physical properties of the matter. One may need additional dynamical equations for the matter to make the system determine, as well as Equation (9).

This can all be worked out using any time surfaces (that is the merit of the ADM formalism); in particular, one can choose a unique gauge by specializing the time surfaces and flow lines to those defined earlier:

1. Choose the flow lines to be Ricci eigenlines:

$$T^\mu_0 = 0 \Rightarrow R^\mu := -2\pi^\mu_j = 0.$$

This algebraically determines the shift vector $N^i(x^j)$, solving the constraint equations (Eq. (6));

2. Determine the lapse function $N(x^j)$ by the condition that the time parameter $t$ measures proper time $\tau$ along the fundamental flow lines:

$$ds^2 = -d\tau^2 \rightarrow N^2 = 1 + N_{i}\bar{N}^i.$$  

These conditions uniquely determine the lapse and shift. Then,

- given equations of state and dynamical equations for the matter, Equations (7)–(9) determine the time evolution of the metric in terms of proper time along the fundamental flow lines;
- and the constraints (Eqs. (5) and (6)) are conserved because of energy–momentum conservation (Eq. (9)).

The development of spacetime with time thus takes place just as is the case for other physical fields, with the relevant time parameter being the proper time $\tau$ along the fundamental flow lines. There is no
problem with either the existence or the rate of the passage of time. The spacetime develops accordingly via Equations (7) and (8).

**Predictability.** Do these equations mean that the spacetime development is uniquely determined for the future and the past from initial data? That all depends on the equations of state of the matter: one can have an equation of the state that involves random elements, as in the example in Figure 3.

The equations determine the time evolution of the spacetime, but do not guarantee predictability. Indeed, if quantum unpredictability gets amplified to macroscales, the spacetime evolution is intrinsically undetermined until it happens, as occurred, for example, during the generation of seed inhomogeneities in the inflationary era in the very early universe from quantum fluctuations (Fig. 4), 26–28 as originally pointed out by Mukhanov. 35

**The issue of time-like surfaces**

In an inhomogeneous realistic spacetime, the surfaces $S$ as determined earlier can become time-like in some regions, and require a time-like version of the initial-value problem for that segment of $S$.

The same problem arises when initial data are set on a time-like finite infinity used to investigate isolated systems such as stars in GR. 13 Friedrich and Nagy 36 have developed the initial-value problem for time-like surfaces in that context in the vacuum case, and the same methods should apply in this situation. Interesting geometric issues arise when $S$ can possess both time- and space-like subsets; however, they should not be insuperable, as Ref. 36 shows.

**The issue of scale**

The above discussion, in principle, applies to all scales. However, gravity is a very weak force, and only large masses have significant effects on spacetime curvature. For that reason, the scale to which the above-mentioned discussion is relevant is scale 3 in Table 1: the scale of astronomical bodies is the scale that determines the structure of spacetime. Smaller-scale entities have a negligible effect on this structure; rather, entities at those scales just respond to spacetime curvature that is fixed at other scales. The spacetime geometry at cosmological size (scale 4), however, is determined by coarse graining or averaging 37 that at astronomical scales (scale 3). This is discussed further in the section “The meshing of scales.”

**Quantum dynamics and nonunitary evolution**

Quantum physics applies both to matter in the universe and to the spacetime structure of the universe itself. We consider them in turn.

**The quantum dynamics of matter in the universe**

Now we consider quantum dynamics in an existing spacetime structure, that is, scale 1 dynamics (Table 1). It is often claimed that quantum physics is unitary, hence the future is determinate. As stated earlier in the section “The problems,” this ignores fundamental features of quantum theory. QM applied to the real universe does not only involve unitary transformations. Measurements happen; collapse of the wave function takes place; classical outcomes occur. This is not just decoherence, which effectively gets rid of entanglement but not superpositions.

**Measurement.** QM is experienced as nonunitary and irreversible when measurements take place or, more generally, when wave function projection happens. 14,15,24,25 This is the core of the local flow of time: the indefinite future becomes the definite past as wave function collapse takes place. This happens all the time everywhere; it does not need to relate to an experiment. If a measurement of an observable $A$ takes place at time $t = t^*$, initially the wave function $\psi(x)$ is a linear combination of eigenfunctions $u_n(x)$ of the operator $\hat{A}$ that represents $A$ for $t < t^*$; the wave function is

$$\psi_1(x) = \sum_n c_n u_n(x).$$

But, immediately after the measurement has taken place, the wave function is an eigenfunction of $\hat{A}$:

$$\psi_2(x) = a_N u_N(x)$$

for some specific value $N$. The data for $t < t^*$ do not determine the index $N$; they merely determine a probability $p_N$ for each possible outcome (Eq. (13)) labeled by $N$, through the fundamental equation

$$p_N = c_N^2.$$  

One can think of the projection of the initial state (Eq. (12)) to the eigenstate (Eq. (13)) as probabilistic time-irreversible collapse of the wave function, with probabilities given by Equation (14).
initial state (Eq. (12)) does not uniquely determine the final state (Eq. (13)), and this is not due to lack of data, it is due to the foundational nature of quantum interactions—or at least it is indubitably the way QM is determined to happen by experiments in a laboratory, whatever its foundations. You can predict the statistics of what is likely to happen but not the unique actual physical outcome, which unfolds in an unpredictable way as time progresses: you can only find out what this outcome is after it has happened.

This happens whenever a classical outcome occurs: for example, when a photon releases an electron in a rhodopsin or chlorophyll molecule; it does not depend on an observer. An example is the set of classical particle images appearing on the screen depicted in Figure 1 as individual particles arrive. Each such individual image is, in effect, a quantum measurement stating that an electron arrived here and deposited energy at this particular place at a particular time. This completely resolves the initial uncertainty as to where the electron would arrive. Nonunitary transformations certainly take place; ignoring this is ignoring a fundamental feature of physics.

We also cannot retrodict to the past at the quantum level, because once the wave function has collapsed to an eigenstate, we cannot tell from its final state what it was before the measurement. Knowledge of the later state (Eq. (14)) does not suffice to determine the initial state (Eq. (12)) at times $t < t^*$, because the set of quantities $c_n$ are not determined by the single number $a_N$. Real QM is not time reversible.

How does this relate to the EBU idea? The hypothesis is that this is where the flow of time changes to the certainty of the past when collapse of the wave function (Eq. (12)) \(\rightarrow\) (Eq. (13)) takes place. This happens all the time everywhere.

Why should the collapse of the wave function relate to the average motion of matter in the universe? Because it is a contextually dependent effect, determined by the local physical environment, such as the measurement apparatus, or any physical system that causes collapse of the wave function (a screen, leaf, etc.).\(^{11}\) That higher-level environment determines when the context for a wave function collapse has been established. However, this is a scale-dependent statement: that average may look different at different scales (see later).

**Summary.** Hamiltonian dynamics is not all that occurs in quantum physics. Irreversible nonunitary transformations (i.e., Eq. (12) \(\rightarrow\) Eq. (13)) also take place, and mark the change from probabilistic predictions to definite outcomes. If this did not happen, the wave function would have no meaning, as it would not predict anything via Equation (14). No events would occur that would make up a statistical ensemble.

The events at scale 1 then underlie emergence of structures and function at scale 2; thus, they underlie the emergence of time at that level.\(^{11}\)

**Quantum gravity and spacetime structure**

As regards quantum gravity, the GR results discussed earlier (scale 3) must emerge from an underlying quantum gravity theory (scale 0). This, presumably, is due to collapse of the quantum gravity wave function to actualize the future from the present boundary of the universe. When we have clarified in whatever way classical GR emerges from this as-yet unknown theory of quantum gravity, this will help establish how the classical spacetime emerges from the underlying quantum gravity fields, whatever they are.

I will not speculate on these topics here except for making a few remarks.

**No universal wave function.** The following questions have been raised by critics. If the universe as a whole (the present-front) undergoes collapse at the present boundary, what causes the collapsing? What is “measuring” the entire universe? In other words, which interpretation of quantum is presupposed here?"\

This paper assumes that the standard view of collapse of the wave function, as discussed earlier, applies even to quantum gravity, with the following nuance: nothing is measuring the entire universe; indeed, there is no useful universal wave function. Rather, local wave functions (at scales 0 and 1) exist everywhere describing local systems, and local measurements take place based on these local wave functions; larger-scale effects (at scales 2 and 3) emerge from these smaller-scale effects by coarse graining.\(^{11}\) Insofar as a global wave function exists, it is an emergent state arising out of all the existing local wave functions, and its dynamics derive from that feature.
It will not be expected to evolve in a unitary way because nonunitary local measurements of local wave functions take place, which will generically lead to a nonunitary evolution of their tensor product. No measurements of this wave function as a whole take place: there is no context in which that could occur. It evolves through bottom-up processes.

Those who disagree with this proposal are invited to propose an experiment that would prove the existence of a wave function of the universe that evolves in a unitary way (the proposal that it does exist is an extraordinary extrapolation from laboratory scale to the scale of the whole universe: such an extrapolation surely needs experimental exploration, else it is just a philosophical speculation).

A preferred reference frame. Another possible objection to this view would be that, if collapse happens, this must be supposed to provide a preferred frame, which needs to be justified; but there is nothing inherent about collapse that provides a preferred frame. However, this puts the thing the wrong way round. It is the local context that defines local preferred frames: they then set the context for wave function collapse to occur, as discussed in Ref. 11.

A consistency condition. The proposal here will be that whatever foundations are set at the quantum gravity level must lead to emergence of an EBU at the macrolevel, or it is an inadequate theory. This is to be taken as a selection rule for theories of quantum gravity.

Indeed, quantum gravity can be based on EBU-like models, such as spin-foam models based on a discrete spacetime picture, which would seem to be a promising approach.

The meshing of scales

The proposal made here is to use proper time along a preferred timeline as the time of evolution for the EBU, but the issue then is, on what scale of description? The answers have been implicit earlier. The point that emerges is that we must distinguish between the emergence of the spacetime itself and the concretization of events within spacetime.

As far as spacetime is concerned, the effective time fixing the EBU structure must be determined on the scale that controls spacetime structure, that is, this determination must take place on the basis of the matter distribution at scale 3, even though the wave function collapse leading to its existence must be based on quantum gravity processes (scale 0).

As far as macroentities at scale 2 are concerned, they experience the proper time determined by the spacetime structure, but have negligible influence on that structure. The present time for them, when the indeterminate future concretizes to the determinate past at this scale, must obviously lie within the spacetime domain that has come into existence, but need not necessarily coincide with the gravitational present. It will emerge from the underlying quantum (level 1) structures, where, because of evidence provided by delayed-choice experiments, the emergent present may be expected to have a crinkly nature characterized as a crystalizing BU (CBU) structure.

The proper time for individual observers who move relative to the universal rest frame defined at scale 3 will not necessarily coincide with the universal proper time. But this is just the same as in SR: individual proper times between spacetime events, determined at scale 2, differ according to the path traveled between them. Time dilation takes place between universal time (scale 3) and local times (scale 2). It is the former that determines the spacetime structure. However, the determination of the effective present at scale 2 is based on quantum processes at level 1.

Accordingly, the implication is that we must distinguish global time—related to the emergence of spacetime itself and determined by level 3 entities, from local time—which relates to the experience of time at the macrolevel (level 2) and is emergent from the underlying level 1 entities. These two are logically distinct, because they have different physical bases. It is possible in GR to have twins part company and rejoin to shake hands at different ages. Their ages will, in general, not coincide with the macro present, which is determined by an average motion of matter at the macroscale 2, because this sets the context for wave function collapse events at scale 1 to take place.

Consistency conditions

These need careful consideration: here are a few preliminary remarks. The basic consistency requirement is that the local time for moving observers cannot give greater times than global time. The surface where local time crystalizes must lie within the evolving future boundary of the EBU. Level 2
time emerges from level 1, where time is crinkly, as pointed out by Ellis and Rothman: some local regions crystalize out later than others, owing to delayed-choice effects. How this happens can only be clarified when we have a good theory of wave function collapse.

The main point I make here is that, as remarked earlier, we can expect wave function collapse to be in some sense controlled by the local scale-2 context. This should lead to consistency between level-1 and level-2 views of the present. However, level-3 time emerges from level 0, but no one has a theory of wave function collapse at the quantum gravity level: the issue is not even discussed in quantum gravity texts, except perhaps to propose the Everett many-worlds view. But that view is incompatible with the usual BU picture, as pointed out earlier.

A very interesting topic is how this all relates to the psychological perception of time, where many experiments show various apparent anomalies. That is a great topic for future investigation.

The EBU sets a direction of time

The EBU provides a cause for a unique direction of time: namely, that the past exists and is developing to the future, which does not yet exist. The future cannot affect us today, because it is not yet definite what it will be. Future possibilities exist, constrained by conservation laws, but not specific outcomes. At the macroscale, causal effects do not reach back to us from the future. The past affects us today in many ways: for example, the heavy elements on Earth, cosmic ray particles causing genetic mutations, and the cosmic background radiation we detect at the present time all originated in the determinate past.

The direction of time arises fundamentally because the future does not yet exist, but the past does: a global asymmetry in the physics context. One can be influenced at the present time from many causes lying in our past, as they have already taken place and their influence can thereafter be felt. One cannot be physically influenced by causes coming from the future, for they have not yet come into being. This is the rationale for saying that the past exists but the future does not: if something can influence you, it exists. The direction of time is nonlocally determined: it points from the start of universe, which is a fixed unchanging past boundary to spacetime, to the ever-changing present, where the future end point of spacetime is continually extending to the future.

Special initial conditions set the thermodynamic arrow of time

The electromagnetic and quantum field theory arrows of times must necessarily be aligned with the global direction of time provided by the EBU, because only retarded Green’s functions can have meaning in the EBU context. We must, however, have had special initial conditions at the start of the universe (a past condition) for the second law of thermodynamics to hold in the forward direction of time. This then aligns the other local arrows of time (chemistry, biology, and the mind) with the direction of time provided by the evolution of the universe. The arrows of time cascade down to lower levels of scale by top-down effects, and then up through complex structures by emergent effects.
**Chronology protection**

A long-standing problem is that, as demonstrated by Gödel, closed time-like lines can occur in exact solutions of the Einstein field equations with reasonable matter content. This opens up the possibility of many paradoxes, such as killing your own grandparents before you were born and thus creating causally untenable situations. It has been hypothesized that a chronology-protection condition would prevent this happening. This is, however, an add-on to the Einstein field equations: an ad-hoc condition added on as an extra requirement on solutions of the Einstein field equations, which do not by themselves give the needed protection.

The EBU automatically provides such protection, because creating closed time-like lines requires the undetermined part of spacetime intruding on regions that have already been fixed. This would require the fundamental world lines defined at scale 3 to intersect; but if these fundamental world lines intersect, the density diverges and a spacetime singularity occurs. The world lines are then incomplete and time comes to an end there; so no “grandfather paradox” can occur because there are no relevant world lines that individuals can move on. Hence, the EBU, as outlined earlier, automatically provides chronology protection. Indeed, we get only spacetimes with global time orientation in the Cauchy development of the initial data surface.

Two comments are in order here. First, individual macro-objects cannot cause spacetime curvature leading to closed time-like lines, as in the case of the Gödel universe, because they are not large enough to significantly curve spacetime. They can only explore the spacetime that exists, and in an EBU that cannot have closed time-like lines, as just explained. Hence, there is no danger of a meeting of individual persons causing a singularity. Second, a paper considered quantum theory experiments to test for the existence of closed time-like curves (CTCs), stated to be trajectories in spacetime that effectively travel backward in time. However, this paper does not relate to CTCs created by the global spacetime structure: rather it relates to trajectories in Minkowski spacetime, where, as already remarked, quantum field theory allows effects that appear as if they relate to travel into the past. This relates to the idea of the existence of a CBU at scale 1, which is compatible with what is discussed here.

**A more realistic view and objections**

Physics needs to take everyday reality into account; hence whatever the microfoundations may be, they must lead to emergence of an EBU at the macrolevel (scale 2). It must also take quantum physics seriously, so there must be an EBU at the microlevel (scale 1; Fig. 1). This then leads to an EBU at the astronomical level (scale 3) because of the inflationary phase in the early universe (Fig. 2).

**Objections**

The main objection to the EBU (the lack of preferred surfaces of change) has been answered earlier. A further set of objections have been made to the proposal, which I now answer.

**Objection 1: time does not flow.** It has been claimed that “Time does not flow: this is incoherent.” This is correct: time does not flow, which suggests it is moving past something else, it passes, meaning that the future boundary of spacetime ever includes more events on an ongoing basis as the potential of the future becomes the reality of the past. It is the passage of time that allows rivers to flow and other events to take place.

**Objection 2: time cannot have a rate.** A key question is, “How fast does time pass?” Davies and others suggest there is no sensible answer to this question. I claim that the answer is given by the metric tensor $g_{ij}(x^k)$, which determines proper time $\tau$ along any world line by Equation (2). This is the time measured locally along that world line by any perfect clock. This is what fixes physical time, including gravitational time dilation (gravitational potential affects relative rates), along world lines. Real world clocks—oscillators that obey the simple harmonic equation—are approximations to such ideal clocks, and it is the relation between such clocks and other physical events that measures the passage of time. The global rate derives from the combination of these local rates.

A more specific version of this claim is the statement “Time cannot pass at the rate of one second per second because that is not a rate, it is a dimensionless number.” This is wrong. The situation is just like rates of exchange of money: this is an operator with two slots, each with its own units; they do not cancel, as pointed out by Maudlin. Hence, time passes at the rate of one second per second,
as determined by the metric tensor locally at each event. There is no inconsistency.

**Objection 3: it is not necessary to describe events.** Davies⁹ and Rovelli⁷ claim that time does not pass because it is not needed to describe the relations between relevant variables, which are all that matter physically. Thus, you can always get correlations between position \( p(t) \) and momentum \( q(t) \) for a system by eliminating the time variable: solve for \( t = t(q) \) and then substitute to get \( p(t) = p(t(q)) = p(q) \), and time has vanished! Thus, time may exist but it does not flow; only correlations matter.

But the latter model leaves out part of what is happening: that does not mean it does not happen, it just means it is a partial model of reality, including some aspects and omitting others. It is a projection from spacetime to a phase portrait. It leaves out the way that the continually changing correlations flow smoothly one after another in a continuous ongoing way. Take, for example, Kepler’s three laws of planetary motion. If only relations between dynamic variables count, not time, one is reduced to Kepler’s one law and miss two-thirds of his discoveries! Yes, of course, it is relative to clocks. Their ticking measures the passage of time. Without the passage of time, they do not tick.

**Objection 4: categorization problem.** A philosophical argument by MacTaggart⁵⁰ and Price¹ is that the past, present, and future are exclusive categories, so a single event cannot have the character of belonging to all three.

The counter is as follows: suppose \( E \) happens at \( t_E \). At time \( t_1 < t_E \), \( E \) is in the future; at time \( t_2 = t_E \), \( E \) is in the present; and at time \( t_3 > t_E \), \( E \) is in past. Its category changes—that is the essence of the flow of time—so this is a semantic problem, not a logical one. One needs adequate semantic usage and philosophical categories to allow description of this change: language usage cannot prevent the flow of time!

**Objection 5: unitary dynamics.** The claim is made that spacetime develops according to Hamiltonian (unitary) dynamics.⁶ I have dealt with this earlier—this is only true if you ignore collapse of the wave function at the microlevel, and all irreversible processes at the macrolevel, in essence claiming they are not really irreversible. Experience dictates otherwise. That is not true in terms of descriptions at each of those levels.

A particular case is the claim that the Wheeler–de Witt equation, which is essentially the Hamiltonian constraint turned into a quantum operator acting on “the wave function of the universe,” only gives time-independent solutions, hence time does not flow. However, this proposal is problematic ᵅ¹ because (1) the argument ignores the issue of measurement, without which the wave function has no meaning unless one tries to go the Everett multiverse path, which has great difficulty with realizing the Born rule (Eq. (14)) as well as a preferred basis problem; (2) the equation has definitional and divergence problems; (3) there is no experimental evidence that the equation actually applies to any real physical systems in any context whatever; and (4) there is no evidence that unitary quantum theory applies to the entire universe, as is implied by the idea of the wave function of the universe. This is an extraordinary extrapolation from the microphysical domain where quantum theory has been shown to apply. In the end, the fact that time does indeed pass shows that this equation does not by itself adequately represent the dynamics of spacetime structure.

**Objection 6: delayed-choice experiments.** Delayed-choice experiments indicate that quantum effects can to some degree reach back into the past, and the EBU does not take this into account.⁵⁰–⁴² The response is that the EBU picture can be modified to the CBU idea, where local delays in actualization take this into account.²

**A more realistic view**

Physics needs to take everyday reality into account. Did it make sense for the Planck satellite team to announce the present age of the universe as 13.784 Gyr on March 21, 2013?²² And, is the universe at the time of writing a bit more than one year older?

This paper proposes that both of these make sense, because spacetime is an EBU, with the present as the future boundary of spacetime, which steadily extends into the future as time progresses. The present separates the past (which already exists) from the future (which does not yet exist, and is indeterminate because of foundational quantum uncertainty). To consider this properly, one must carefully consider the various scales that characterize
physical structure, and distinguish global and local time, as discussed earlier.

There are some technical aspects to this, which have been explained earlier—namely, (1) simultaneity is a purely psychological construct; (2) one can define unique surfaces of change in a nonlocal geometric way; (3) this structure prevents existence of closed time-like lines; and (4) the arrow of time is distinguished from the direction of time, which is nonlocally defined in this context. There are three technical issues that need development. The first is how the initial-value problem works when these surfaces become time-like, and this is an unusual situation that will need careful thought, but initial work by Friedrich and Nagy\(^36\) shows that it can be done. The second is careful further consideration of how this works at the various levels of structure and scale, and how they relate to the passage of time (as mentioned above) and the arrow of time (as in Ref. 4). The third is proposing a viable theory of wave function collapse. Various initial proposals are promising in this regard, but need improvement.

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**Conflicts of interest**

The author has no conflicts of interest.

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