From time to timescape – Einstein's unfinished revolution

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I argue that Einstein overlooked an important aspect of the relativity of time in never quite realizing his quest to embody Mach's principle in his theory of gravity. As a step towards that goal, I broaden the Strong Equivalence Principle to a new principle of physics, the Cosmological Equivalence Principle, to account for the role of the evolving average regional density of the universe in the synchronisation of clocks and the relative calibration of inertial frames. In a universe dominated by voids of the size observed in large-scale structure surveys, the density contrasts of expanding regions are strong enough that a relative deceleration of the background between voids and the environment of galaxies, typically of order $10^{-10}\mathrm{ms}^{-2}$, must be accounted for. As a result one finds a universe whose present age varies by billions of years according to the position of the observer: a timescape. This model universe is observationally viable: it passes three critical independent tests, and makes additional predictions. Dark energy is revealed as a mis-identification of gravitational energy gradients and the resulting variance in clock rates. Understanding the biggest mystery in cosmology therefore involves a paradigm shift, but in an unexpected direction: the conceptual understanding of time and energy in Einstein's own theory is incomplete.

I. INTRODUCTION

In 1905 Einstein completely changed our understanding of the nature of time. Rather than being an absolute standard independent of the physical objects in the universe, time became an intrinsic property of the clocks carried by the objects themselves. In comparing two clocks, time could stretch and bend depending on the relative speeds of particles over their histories.

One hundred years later we find ourselves in a circumstance with echoes of a century before. Einstein's first revolution, special relativity, overthrew the then popular aether theories which had been invented to try to come to grips with the difference between Maxwell's equations for the propagation of electromagnetic waves on one hand, and Newton's mechanics on the other. The historical parallels today are striking. Whereas once the Michaelson–Morley experiment provided evidence that the Newtonian worldview was flawed, present cosmological observations suggest that the expansion rate of the universe is accelerating, posing a foundational problem for our understanding of physics. Again the first solution that physicists have jumped to is to suppose the existence of some mysterious fluid, "dark energy", which permeates the fabric of space, the 21st century aether.

In this essay I will argue that just like 100 years ago, the real physics needed to solve the conundrum of dark energy does not involve a fluid in the vacuum of space but a deepening of our understanding of the nature of time, in a manner which many physicists find counter-intuitive. In particular, time as described by Einstein's second revolution, the general theory of relativity, is deeply more subtle than the naïve quasi-Newtonian concept that is applied in the current standard model of cosmology. The completion of Einstein's second revolution will, I argue, change our understanding of the universe and the foundations of physics, by a better understanding of time.

The reason that physicists are quick to invent new forces when confronted with "dark energy", or even to modify gravity in ways that could change solar system physics, is that we usually think of general relativity as a completed theory. Yet without even going to the strong field regime, where the singularity theorems tell us general relativity does break down, there are deep subtleties in the definition of energy and momentum in general relativity, which have never been satisfactorily resolved.

The subtleties, which Einstein and many a mathematical relativist since have wrestled with, have their origin in the equivalence principle, which means that we can always get rid of gravity near a point. As a consequence, the energy, momentum and angular momentum associated with the gravitational field, which have macroscopic effects on the relative calibrations of the clocks and rods of observers, cannot be described by local quantities encoded in a fluidlike energy-momentum tensor. Instead they are at best *quasilocal* [1].

A simple way to understand this is to recall that in the absence of gravity energy, momentum and angular momentum of objects obey conservation laws. A conservation law simply means that some quantity is not changing with time. *But whose time?* In general relativity, a dynamical theory of spacetime, where space and time bend and warp in an evolving manner, a definition of what is changing or not changing depends on how we split spacetime into spatial hypersurfaces which evolve with time, and how we choose particular canonical observers on such surfaces whose clocks are to measure the changes. Since the mathematical structure of general relativity – its diffeomorphism invariance – does not depend

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on such choices of observer frames, there is no unique way to define conservation laws.

The "quasilocality" of gravitational energy and momentum is very different to a nonlocality of interactions in flat spacetime which some physicists occasionally postulate and which is anathema to many, myself included. General relativity is entirely local in the sense of *propagation* of the gravitational interaction, which is causal. Indeed it thereby overcomes the nonlocality problem of Newtonian gravity: there is no action at a distance. However, the curved background on which the interaction propagates may contain its own energy and momentum, when integrated over sufficiently large regions, and this has to be understood in the calibration of local rods and clocks at widely separated events. In dealing with the structure of the whole universe it is inevitable that we deal with separations on the largest scales possible.

Since the definition of quasilocal gravitational energy and momentum [1] depends on spacetime splits that are inherently noncovariant and nonunique, many questions of naturalness of any particular definition arise. There is a dilemma that any spacetime split inevitably breaks a given particle motion into a motion *of* the background and a motion *with respect to* the background; and this may involve a degree of arbitrariness.

The question we are faced with is: which choices of frame have the greatest utility for the physical description of the universe? I adopt the view that since quasilocal gravitational energy gradients have their origin in the equivalence principle, the primary criterion for making such identifications is that the equivalence principle itself must be properly formulated, and respected, when making macroscopic cosmological averages.

II. EINSTEIN'S UNFINISHED PRINCIPLE

In laying the foundations of general relativity, Einstein sought to refine our physical understanding of that most central physical concept: *inertia*. As he stated: "In a consistent theory of relativity there can be be no inertia relatively to 'space', but only an inertia of masses relatively to one another" [2]. This is the general philosophy that underlies Mach's principle, which strongly guided Einstein. However, the refinement of the understanding of inertia that Einstein left us with in relation to gravity, the Strong Equivalence Principle, only goes part-way in addressing Mach's principle.

Einstein's conceptual route began with the *Weak Equivalence Principle* or the *Principle of Uniqueness of Free Fall*, known since the experiments of Galileo, that *all bodies subject to no forces other than gravity will follow the same paths given the same initial positions and velocities*. Realising that this phenomenological observation implies a universality for gravity unlike that of other interactions, Einstein sought to establish gravitation as a property of a dynamical spacetime structure. His first step towards that goal was the *1907 Equivalence Principle* [3]: *All motions in an external static homogeneous gravitational field are identical to those in no gravitational field if referred to a uniformly accelerated coordinate system.* In a small sealed region, an observer on the Earth's surface cannot perform experiments observationally distinguishable from those in a rocket moving with acceleration, $\mathbf{g}$. This is because observers on the Earth's surface are not inertial observers, but accelerated observers pushed up by the static forces of the earth beneath our feet. The natural state is free fall.

The *Strong Equivalence Principle* (SEP) then is the statement that even in an arbitrary gravitational field, by a choice of local coordinates we can always always find a frame corresponding to the natural state of free fall: *At any event, always and everywhere, it is possible to choose a local inertial frame (LIF) such that in a sufficiently small spacetime neighbourhood all non-gravitational laws of nature take on their familiar forms appropriate to the absence of gravity, namely the laws of special relativity.* Since we can always eliminate the effects of gravity near a point, instead of being a force in a pre-existing space gravity becomes a feature of spacetime structure. Space and time can curve and bend, and the mathematical object that describes the bending, the connection, tells us how to relate clocks and rods of freely falling particles at widely separated events.

This is not the whole story, however, because as yet it tells us nothing about the spacetime structure of our actual universe. For that we need to solve Einstein's field equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{1}$$

to obtain the Einstein curvature tensor, $G_{\mu\nu}$, corresponding to the distribution of matter sources in the energy-momentum tensor, $T_{\mu\nu}$. The connection of general relativity then depends – via solutions of Einstein's equations – on the evolving distribution of matter.

Provided we have solved (1) over cosmological scales for the observed universe, we have addressed Mach's principle which may be stated [4, 5]: *"Local inertial frames are determined through the distributions of energy and momentum in the universe by some weighted average of the apparent motions"*. But Einstein never completed the task of addressing Mach's principle, as he did not specify what is to be understood by the "suitable weighted average" of the evolving distribution of all the matter fields that can influence the geometry at any event.

My thesis here is that a further refinement in the understanding of inertia needs to be made to clarify Mach's principle in relating local frames to the global universe and to solve equations (1) on cosmological scales. If one views the Einstein equations as specifying a 4–dimensional continuum completely determined for all space and all time, if we only knew the distribution of matter, then the need for further refining the equivalence principle is easily overlooked. However, general relativity is a causal theory, and the universe had a beginning.

The geometry at any event can only depend on processes *within* its past light cone, limited by the finite age of the universe. Thus the Einstein equations should be viewed as dynamical evolution equations for the geometry, limited by initial conditions with statistical fluctuations.

Einstein overlooked the possibility of further refining the notion of inertia via the equivalence principle, since the idea that the universe had a beginning only became widely accepted decades after he first thought about general relativity. His first journey through the foundational questions of cosmological relativity had him worrying about boundary conditions at spatial infinity instead [2]. But events at spatial infinity outside the past light cone are irrelevant if the universe had a beginning. Although the problem of defining gravitational energy troubled Einstein greatly, and the relation of the geometry of bound systems to expanding space was one whose foundational significance was obvious to him [6], once the expanding universe became accepted he never returned to the equivalence principle with thought experiments like those he had posed in 1907. I will take such steps, but first let us recall current standard practice in cosmology.

III. AVERAGING IN COSMOLOGY

To define a "suitable weighted average of the apparent motions" for Mach's principle requires that we understand the relation between local regional geometry and average geometry on cosmological scales [7]. In solving Einstein's equations for the universe our standard cosmology still takes the simplifying assumption, made in the first models of Einstein, Friedmann and Lemaître 80–90 years ago, that the structure of the universe can be ignored on average, and matter treated as a homogeneous isotropic fluid. By the evidence of the uniformity of the cosmic microwave background (CMB) radiation, the universe certainly did satisfy this approximation when the universe was a few hundred thousand years old and the first atoms formed. The perturbations in baryons and photons then had an amplitude $\delta\rho/\rho \sim 10^{-5}$ above the mean density, and the amplitude of perturbations in nonbaryonic dark matter was probably only one to two orders of magnitude stronger.

At the present epoch, however, following the growth of complex structures from gravitational collapse, the universe is only statistically homogeneous if sampled on large scales of order 150–300 Mpc. A box of the size of statistical homogeneity may be as small as $100h^{-1}$ Mpc, where h is the dimensionless parameter related to the Hubble constant by $H_0 = 100h\,\mathrm{km\ sec^{-1}\,Mpc^{-1}}$. But within such a box density contrasts $\delta\rho/\rho \sim -1$ are observed over scales $30h^{-1}$Mpc, which is the typical diameter of voids which form 40%–50% of the volume of the present universe [8]. If we include the numerous minivoids of smaller diameters, then the volume of the present universe is dominated by empty voids, while clusters of galaxies are spread in a cosmic web of bubble-like sheets that surround the voids, and thin filaments that thread them.

Over the scales on which $|\delta\rho|/\rho \sim 1$ in expanding regions, we can expect commensurate gradients in Ricci spatial curvature. Our standard cosmology by contrast assumes a uniform Ricci scalar curvature, and in applying it we implicitly assume we can ignore spatial curvature gradients and variations of the relative calibrations of clocks and rods of observers within cells coarse grained at the scale of statistical homogeneity, $100h^{-1}$ Mpc. Such an assumption, which effectively assigns one single cosmic time to the whole universe, has been made for convenience for 80–90 years but is not deeply grounded in theoretical concepts or observational fact.

One reason that the assumptions of the standard cosmology are not often questioned, despite the evidence of our telescopes, is that cosmological gravitational fields are weak due to low average densities of matter. It is commonly believed that as long as we are in the weak-field limit that we do not have to worry about the space and time distorting complications of general relativity, as they only become important near very compact objects such as neutron stars or black holes. What is forgotten, however, is that the weak-field limit is always taken about a background, and once inhomogeneities develop in the universe there are no exact symmetries to describe the background.

In the absence of an exact symmetries, mathematically described by Killing vectors, there is no general solution to the problem of how to keep two clocks synchronized in general relativity. Our usual intuition about strong and weak gravitational fields is based on asymptotically flat solutions such as the Schwarzschild and Kerr geometries which have an exact time symmetry. Since the universe is expanding, however, no time symmetry exists absolutely. I will argue that in the absence of such a symmetry a small relative deceleration of average regional backgrounds can cumulatively lead to large variations in the clock rates of canonically defined observers.

Numerical simulations of cosmic structure made on large supercomputers today assume only Newtonian gravity in the background of an expanding homogeneous universe, whose expansion rate is given by that of a Friedmann–Lemaître–Robertson–Walker (FLRW) model put in by hand. The deceleration of the local expansion is not directly coupled to the motion of the mass particles as it would be in Einstein's equations.

At this point I believe we have overlooked a crucial foundational question. To make the Newtonian approximation, we must first make the weak field approximation about a suitable static Minkowski space. But given that the universe is not static, in choosing an appropriate Minkowski frame we first have to answer the question: what is the largest scale on which the SEP can be applied?

IV. THE COSMOLOGICAL EQUIVALENCE PRINCIPLE

My proposal for applying the equivalence principle on cosmological scales is to deal with the average effects of the evolving density by extending the SEP to larger regional frames while removing the time translation and boost symmetries of the LIF as follows [9]:

At any event, always and everywhere, it is possible to choose a suitably defined spacetime neighbourhood, the cosmological inertial frame (CIF), in which average motions (timelike and null) can be described by geodesics in a geometry that is Minkowski up to some time-dependent conformal transformation,

$$\mathrm{d}s^2_{\mathrm{CIF}} = a^2(\eta)\left[-\mathrm{d}\eta^2 + \mathrm{d}r^2 + r^2(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2)\right]. \quad (2)$$

This statement of the Cosmological Equivalence Principle (CEP) reduces to the standard SEP if $a(\eta)$ is constant, or alternatively over very short time intervals during which the time variation of $a(\eta)$ can be neglected. In those cases the CIF (2) reduces to a LIF. The spatially flat FLRW metric (2) is to be viewed as a regional frame, not a geometry for the whole universe.

The SEP says nothing about the average effect of gravity, and therefore nothing about the "suitable weighted average of the apparent motions" of the matter in the universe. Since gravity for ordinary matter fields obeying the strong energy condition is universally attractive, the spacetime geometry of a universe containing matter is not stable, but is necessarily dynamically evolving. Therefore, accounting for the average effect of matter to address Mach's principle means that the relevant frame is one in which time symmetries are removed.

Furthermore, if we are to demand a smooth Newtonian gravitational limit in all circumstances, then we have to accommodate the fact that Newtonian gravity deals with just one scalar source, the density, whereas general relativity is tensorial. This means that we must be dealing with an average spacetime with symmetries in taking a Newtonian gravity limit. The metric (2) removes the time symmetries while preserving the isotropy and homogeneity of space regionally within a CIF.

What has this got to do with inertia? Let us first recall the well-known property that in the case of the volume expanding motions illustrated by Fig. 1, we cannot *locally* distinguish the case of comoving particles at rest in an expanding metric (2) from the case of particles in motion in the static Minkowski space of the relevant LIF if we were to choose Riemann normal coordinates. On local scales, both yield the Hubble law redshift

$$z \simeq \frac{H_0 \ell_r}{c}, \qquad H_0 = \left.\frac{\dot a}{a}\right|_{t_0}$$

where ℓ_r is the radial proper distance from an observer at the origin to a source, and an overdot denotes a derivative with respect to t, where $c\,\mathrm{d}t = a\,\mathrm{d}\eta$. This is true whether the exact relation, $z + 1 = a_0/a$, is used or the radial Doppler formula $z+1 = [(c+v)/(c-v)]^{1/2}$ of special relativity is used, before making a local approximation.

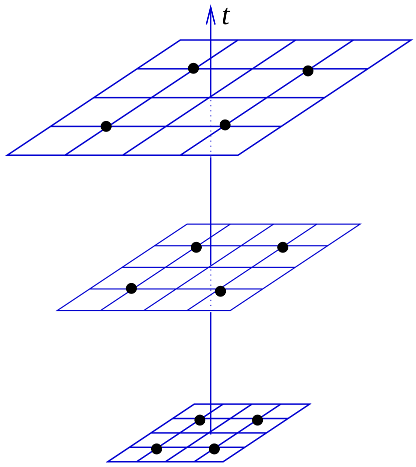

FIG. 1: *A set of particles undergoes an isotropic spatial 3–volume expansion in a spatially flat local region. It is impossible to locally distinguish the case of particles at rest in a dynamically expanding cosmological space from particles moving isotropically in a static Minkowski space. One spatial dimension is suppressed.*

Rather than simply invoking static special relativistic LIFs over short time intervals, the CEP demands that we can always find regional frames (2) for arbitrarily long time intervals during which the motion of the particles is decelerated, $\ddot a < 0$, by the average density of matter. As Einstein demanded, there should only be inertia of masses relative to masses. Since the deceleration of the volume expansion is due to the backreaction of the average density of matter particles in defining their own background, the CEP thus represents a refinement in the understanding of inertia. We can always find regional frames (2) in which the average volume-expanding motion with deceleration is such that *we cannot tell whether particles subject to such motion are at rest in an expanding space, or moving in a static space.* The argument about whether particles are moving or space is expanding is an argument about something that is fundamentally indistinguishable.

V. THOUGHT EXPERIMENTS

Just as with the original 1907 Einstein equivalence principle, the order of magnitude of relevant effects can be determined from thought experiments. To demonstrate this, I will first show that a suitable equivalent of decelerated Minkowski space particles can always be found for the motion of a congruence of comoving particles in (2), even for arbitrarily long time intervals.

A. Semi-tethered lattices

Let us construct what I will call the *semi-tethered lattice* by the following means. Take a lattice of Minkowski observers, initially moving isotropically away from each nearest neighbour at uniform initial velocities. The lattice of observers are chosen to be equidistant along mutual oriented $\hat{x}$, $\hat{y}$ and $\hat{z}$ axes. Now suppose that the observers are each connected to six others by strings of negligible mass and identical tension along the mutually oriented spatial axes, as in Fig. 2. The strings are not fixed but unwind freely from spools on which an arbitrarily long supply of string is wound. The strings initially unreel at the same uniform rate, representing a "recession velocity". Each observer carries synchronised clocks, and at a prearranged local proper time all observers apply brakes to each spool, the braking mechanisms having been pre-programmed to deliver the same impulse as a function of local time.

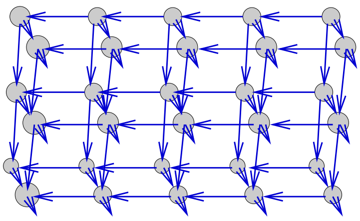

FIG. 2: *The semi-tethered lattice. (See text for description.) The time evolution of the lattice follows a course similar to that of the spatial grid in Fig. 1, with deceleration.*

The semi-tethered lattice experiment is directly analogous to the decelerating volume expansion of (2) due to some average homogeneous matter density, because it maintains the homogeneity and isotropy of space over a region as large as the lattice. Work is done in applying the brakes, and energy can be extracted from this – just as kinetic energy of expansion of the universe is converted to other forms by gravitational collapse. Since brakes are applied in unison, however, there is *no net force on any observer in the lattice*, justifying the *inertial frame* interpretation. Even if the braking function has an arbitrary time profile, provided it is applied uniformly at every lattice site the clocks will remain synchronous in the comoving sense, as all observers have undergone the same relative deceleration.

B. Relative deceleration of regional backgrounds

Let us now consider two sets of disjoint semi-tethered lattices, with identical initial local expansion velocities, in a background static Minkowski space. (See Fig. 3(a).) Observers in the first congruence apply brakes in unison to decelerate homogeneously and isotropically at one rate. Observers in the second congruence do so similarly, but at a different rate. Suppose that when transformed to a global Minkowski frame, with time t, that at each time step the magnitudes of the 4–decelerations satisfy $\alpha_1(t) > \alpha_2(t)$ for the respective congruences. By special relativity, since members of the first congruence decelerate more than those of the second congruence, at any time t their proper times satisfy $\tau_1 < \tau_2$. The members of the first congruence age less quickly than members of the second congruence.

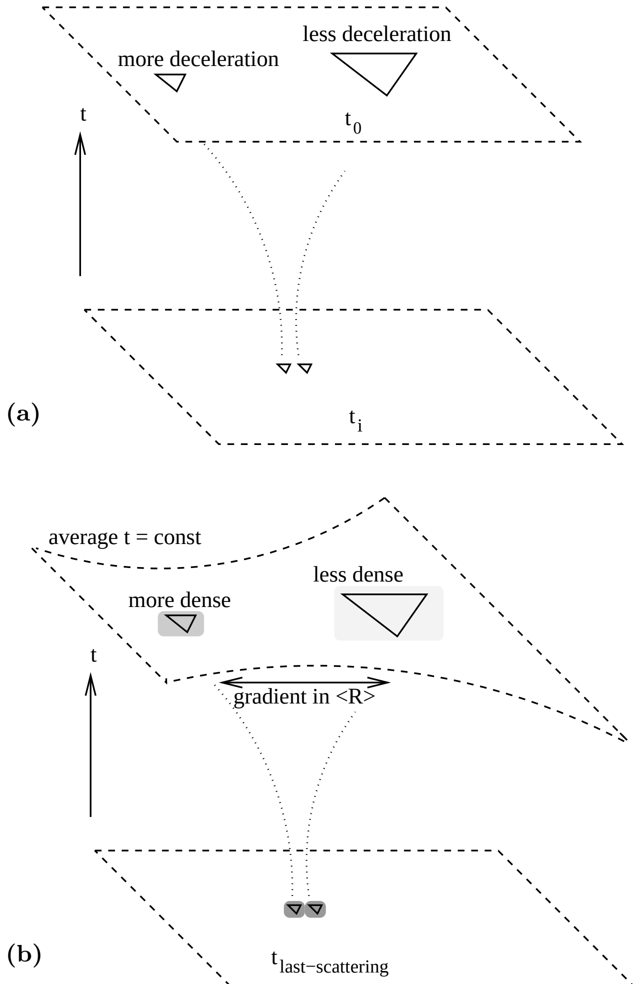

FIG. 3: *Two equivalent situations:* **(a)** *in Minkowski space observers in separate semi–tethered lattices, initially expanding at the same rate, apply brakes homogeneously and isotropically within their respective regions but at different rates;* **(b)** *in the universe which is close to homogeneous and isotropic at last-scattering comoving observers in separated regions initially move away from each other isotropically, but experience different locally homogeneous isotropic decelerations as local density contrasts grow. In both cases there is a relative deceleration of the observer congruences and those in the region which has decelerated more will age less.*

By the CEP, the case of volume expansion of two disjoint regions of different average density in the actual universe is entirely analogous. The equivalence of the circumstance rests on the fact that the expansion of the universe was extremely uniform at the time of last scattering, by the evidence of the CMB. At that epoch all regions had almost the *same* density – with tiny fluctuations – and the same uniform Hubble flow. At late epochs, suppose that in the frame of any average cosmological observer there are expanding regions of *different* density which have decelerated by different amounts by a given time, t, according to that observer. Then by the CEP the local proper time of the comoving observers in the denser region, which has decelerated more, will be less than that of the equivalent observers in the less dense region which has decelerated less. (See Fig. 3(b).) Consequently the *proper time of the observers in the more dense CIF will be less than that of those in the less dense CIF*, by equivalence of the two situations.

The fact that a global Minkowski observer does not exist in the second case does not invalidate the argument. The global Minkowski time is just a coordinate label. In the cosmological case the only restriction is that *the expansion of both average congruences must remain homogeneous and isotropic in local regions of different average density* in the global average t =const slice. Provided we patch the regional frames together suitably, then if regions in such a slice *are still expanding* and have a significant density contrast we can expect a significant clock rate variance.

This equivalence directly establishes the idea of a *gravitational energy cost for a spatial curvature gradient*, since the existence of expanding regions of different density within an average t =const slice implies a gradient in the average Ricci scalar curvature, $\langle\mathcal{R}\rangle$, on one hand, while the fact that the local proper time varies on account of the relative deceleration implies a gradient in gravitational energy on the other.

VI. THE TIMESCAPE AND “DARK ENERGY”

Given the complex structure of voids, walls and filaments described in Sec. III, then if we model the universe that we see we must account for its present epoch inhomogeneity. Buchert’s equations [11] provide a suitable framework for describing the average evolution of Einstein’s equations in an inhomogeneous universe, and give corrections to the Friedmann equations. The interpretation of Buchert’s equations has been controversial [12, 13]. The reason for this stems from the fact that they involve spatial averages. In general relativity we measure invariants of the local metric, and over the scales on which the geometry is inhomogeneous the local metric can vary substantially. Thus every observer cannot be the same average observer. We must account not only for how inhomogeneity affects average evolution, but also for how the variance in the geometry affects the calibration of local clocks and rods relative to the average.

I have developed a new physical interpretation [10] of solutions to the Buchert equations, from the observation that structure formation provides us with a natural split of scales. We and the objects we observe are in galaxies which formed from density perturbations that were greater than critical density, whereas the volume-average location today is in an underdense void. By the CEP we must account for the gravitational energy costs of gradients in spatial curvature between galaxies and the volume-average voids [8] in the relative calibrations of regional clocks.

The relevant average *cosmic rest frame* for the universe is one in which the underlying regional expansion of CIFs remains uniform in terms of the rate of change of local proper distances with respect to local proper times of ideal observers who measure an isotropic CMB [9, 10]. The relation between proper volume and proper diameter is different in regions of different Ricci curvature. Consequently, even though voids open up faster when measured by any one set of clocks, since the clocks of isotropic observers in voids tick faster due to a weaker relative deceleration of their background, there can still be an underlying uniform local Hubble flow.

There is still a Copernican principle: we are average observers for observers in a galaxy. However, the local environment of bound systems which have decoupled from the expansion of space can differ systematically from the local environment within freely expanding space in voids. Observers in both locations can measure an isotropic CMB, but those in voids will measure a cooler mean CMB temperature and an angular anisotropy scale moved to smaller angles on account of differences in gravitational energy and spatial curvature respectively.

Cosmic acceleration is an apparent effect [10, 14] which arises when we mistakenly try to fit a Friedmann model to the whole universe with the incorrect assumption that the local spatial curvature and local clock rates of isotropic observers everywhere are identical to our own. An observer in a void will infer no cosmic acceleration, but observers in galaxies draw different conclusions when converting measured luminosity distances to an acceleration using two derivatives of a different time parameter.

The epoch of onset of apparent cosmic acceleration is intimately tied to the growth of cosmic structure. It begins at a redshift $z \simeq 0.9$ when the void fraction reaches 59% [10, 14]. One finds a model universe [14], which by Bayesian comparison to supernovae data fits at a level statistically indistinguishable from the standard cosmology with a cosmological constant [15]. Furthermore, it matches the angular scale of the sound horizon seen in the CMB anisotropy spectrum, and the comoving scale of the baryon acoustic oscillation [15], and may explain other puzzles. Several tests will enable the model to be distinguished from homogeneous models with dark energy by future experiments [16].

The most startling conclusion is that the age of the universe can vary by billions of years today depending on whether one is an isotropic observer in a void or a galaxy. In a galaxy the best-fit age [15] is about 14.7 billion years, at a volume-average position about 18.6 billion years, and in the centre of a void even larger. This large variance in clocks is counter-intuitive to physicists because we are talking about weak fields. However, in the absence of exact symmetries there is no solution to the problem of clock synchronization in general relativity, even for weak fields. The CEP extends the conceptual principles of general relativity to address this problem in a natural manner. Computing the effect [9] one finds that a small relative deceleration of backgrounds of differently evolving regional densities, typically of order $10^{-10}\mathrm{ms}^{-2}$, cumulatively leads to the differences claimed when integrated over the lifetime of the universe .

In 1905 Einstein established that time was relative, but in assuming simple model universes described by a single global frame, and no structure, we have for the past 80–90 years overlooked the deep possibilities of general relativity, imagining only a universe described by a single cosmic time. A universe as inhomogeneous as the one we observe cannot be adequately described by a single global frame, but if we extend the equivalence principle to admit regional frames (2), in a manner consistent with Mach's principle, then the universe that is revealed [10, 14] is a *timescape* whose age varies with the inhomogeneous geometry, a structure much richer in its beauty and subtleties.

In 1917 Einstein realised that *in the presence of matter the universe must change with time.* Faced with the dilemma that this contradicted the cosmological preconceptions of his time, Einstein introduced a cosmological constant to try to force the universe to be static [2]. I believe that the cosmic mystery of our time, dark energy, requires that we return to first principles and attempt to think in the way Einstein taught us to think, rather than compounding his greatest blunder. If I am correct, then the importance of understanding gravitational energy in relation to the dynamical nature of time and space is potentially of foundational importance for quantum gravity too. Einstein's revolution is not complete.

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