Unification through Generalised Proper Time: The Elementary Construction of the Theory

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Abstract

Unification based upon the generalisation of proper time is proposed as a comprehensive framework to account for the fundamental structure of matter, in a manner contrasting with the more familiar approach based on extra dimensions of space. The elementary properties of matter to be incorporated include the Standard Model of particle physics together with a source for the dark sector and a coherent formalism for quantum gravity. We elaborate upon the manner in which all such material phenomena and empirical properties as distributed in an extended 4-dimensional spacetime can be encompassed within, and derived from, the continuous flow of time alone via a generalised arithmetic form for infinitesimal intervals of proper time. This approach will also be compared and contrasted with the basic structure of causal set theory as a means of demonstrating how it is possible to construct a full physical theory essentially from elements of time alone, as explicitly developed from the most elementary level. The conception of time as utilised and elucidated in this theory, with emphasis upon the causal continuum properties and as the basis for unification, will be clarified.

Keywords: Unification; extra dimensions; causal sets; proper time; Standard Model; dark sector; quantum gravity

Contents

1 Introduction and Outline

The aim of this paper is to paint the big picture concerning how empirical phenomena from the smallest scale of particle physics as studied in the laboratory to the largest scale of cosmology as observed in the universe can derive from the inherent composition of the flow of time alone. Unification in a physical theory is essentially achieved through an analysis of the all-embracing nature of time. Given the seeming implausibility of this ambition this paper is motivated largely to demonstrate how such a construction is possible by explicitly building up the geometric and physical structures involved from the most basic level of infinitesimal elements of time. This approach will be contrasted with the more established framework involving the attachment of extra dimensions of space as well as with the construction of 4-dimensional spacetime itself as a discrete causal set. We shall describe how the new approach based on generalised proper time provides a natural foundation for a unified theory and review the successes in terms of the empirical connections and the explanatory power that has been achieved.

The theory to be presented essentially requires the apparent 'one dimension' of time to be represented in an extended 4-dimensional spacetime form while also providing the source for the extensive variety of matter observed in spacetime. The idea that higher-dimensional structures with elaborate features can be enfolded or encoded in a lower-dimensional entity has a number of familiar precedents. With varying degrees of technicality these include the art of origami (such as employed in 'pop-up' books as alluded to in [1] chapter 1), a traditional umbrella (as mechanically deployed and opened in 3-dimensional space or ideally folded and closed as a one-dimensional object in space), holograms (with a 3-dimensional image optically encoded in a 2-dimensional plane) and autostereograms (with the image of 3-dimensional structures encoded in a 2-dimensional graphic design). These examples give an initial hint of plausibility to the theory to be elaborated here, although the mechanism will be again rather different and in particular involves a deeper understanding of the nature of time itself. Indeed the resulting comprehensive unified physical framework could be considered to arise naturally and simply as a 'theory of time'. The contents of the paper is outlined as follows.

In section 2 we briefly review the alternative but familiar approach of models in which extra *spatial* dimensions are simply *added* over and above a 4-dimensional spacetime to accommodate a material content. By contrast in the present theory we propose that not only matter but also an extended 3-dimensional space can *derive* from the implicit arithmetic substructure of the flow of *time*. Specifically the manner in which a continuous 4-dimensional spacetime itself can be constructed *from* elements of time alone will be elaborated in section 3, utilising an analogy and contrast with the discrete spacetime construction of causal set theory. The natural generalisation of this new approach leads directly to forms of matter in 4-dimensional spacetime, as we describe in section 4 where the empirical successes in connectiong with known properties of matter will also be summarised.

While the above sections focus upon the physical properties of the theory, the second half of the paper also includes elements of philosophical discussion. Central to the identification of the physical structures is the essential role of the perception of phenomena in space as well as in time as prerequisite conditions for constructing an observable universe as we discuss in section 5. A key aspect in understanding this theory is the conception entailed of the nature of time, with emphasis on the causal continuum properties rather than any 'one-dimensional' character, as we describe in more detail in section 6. The suitability and effectiveness of this approach for a unified physical theory will then be elucidated in section 7 in the context of the historical developments towards an ever more unifying framework through novel insights in the relations between space, time and matter. We conclude with further comments in the final section.

2 A Basis in Time rather than Extra Dimensions of Space

Since the innovations of Kaluza and Klein in the 1920s [2, 3] there have been many models, particularly in recent decades (see for example [4, 5]), positing extra spatial dimensions over and above 4-dimensional spacetime as a putative framework for a more unified theory of the properties of matter. The basic structure of a typical model is represented in figure 1 (see also for example [4] figures 1 and 3).

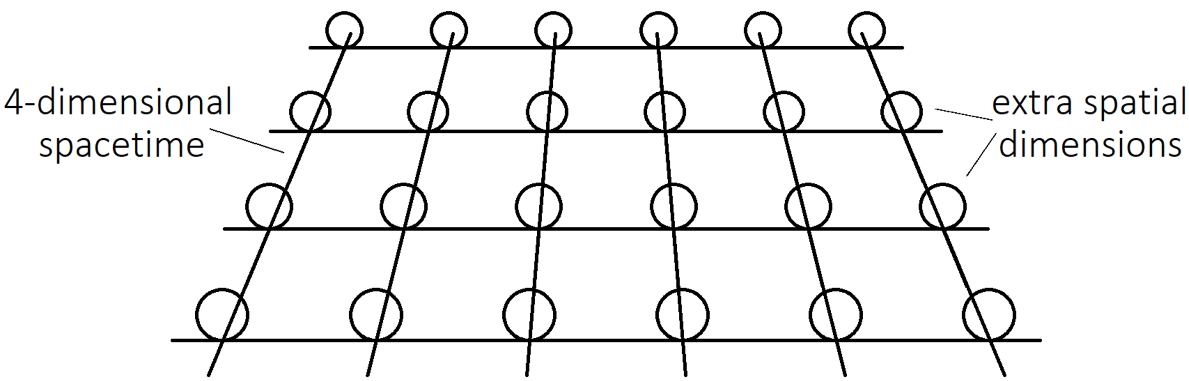

Figure 1: In models with extra spatial dimensions a further $(n-4)$-dimensional space (represented by the circles) is attached to every point of a 4-dimensional spacetime (represented by the grid) in an overall n-dimensional spacetime manifold structure. The properties of the extra dimensions are manifested as the properties of matter observed in the extended and external 4-dimensional base spacetime.

The extra spatial dimensions may be curled up, as pictured and typically on a microscopic scale [4], or indefinitely extended [5]. In either case our own familiar extended 4-dimensional spacetime is embedded in the full n-dimensional 'bulk' manifold. In this bulk space, incorporating the general relativistic geometric property of being everywhere locally flat, an augmented local Lorentzian spacetime structure with an $n \times n$ metric $\hat{\eta} = \text{diag}(+1, -1, \ldots, -1)$ incorporates the extra spatial components as well as the original four preferred spacetime dimensions. The number of the extra dimensions and the overall geometric structure is essentially input by hand, as is the means of extracting our 4-dimensional spacetime base with an apparent matter content and physical properties deriving from the structure of the additional $(n-4)$ spatial components. Every point of the larger bulk space is situated over a unique point of the 4-dimensional base space, with the overall structure of a 'fibre bundle' manifold (see for example [6]), as implied in the construction outlined in figure 1.

By analogy with figure 1 on beginning more minimally with the one dimension of time alone a global 3-dimensional extended flat space could be attached to each point in time as pictured in figure 2.

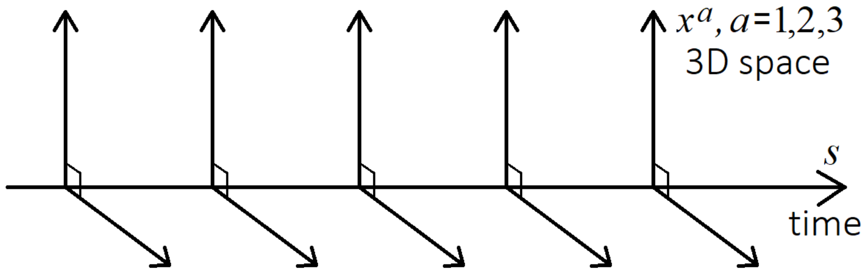

Figure 2: An extended 3-dimensional Euclidean space with three real parameters $\{x^a\}$, represented by pairs of arrowed lines at right-angles, attached to every point of time which itself is represented by the single long arrow. This describes the background structure of Newtonian physics, here with s denoting a universal time parameter.

Every point in this full construction corresponds to a point in a 3-dimensional extended space with a Euclidean metric structure as well as to a unique point in time. This again exhibits the overall structure of a fibre bundle manifold, now with the fibres accommodating the external space and with time alone as the base ([7] figure 17.7(a)). With conceptions of space and time that are independent this structure is hence not realistic in comparison with our own relativistic world but rather corresponds to the Newtonian worldview, as characterised in particular by an absolute time and a universal real continuous time parameter.

By contrast in the theory to be expounded in this paper we begin with the continuous flow of time alone as described by the real continuum:

$$s \in \mathbb{R} \tag{1}$$

and rather than *adding* space we exploit the elementary arithmetic substructure of the real numbers. In particular we note that infinitesimal intervals $\delta s \in \mathbb{R}$ of equation 1 can be *directly* arithmetically expressed in the form (with the summation convention over repeated indices $a, b = 0, 1, 2, 3$ implied):

$$(\delta s)^2 \;=\; +(\delta x^0)^2 - (\delta x^1)^2 - (\delta x^2)^2 - (\delta x^3)^2 \;=\; \eta_{ab}\delta x^a \delta x^b \tag{2}$$

Since we are beginning with time as a *real* continuum $(\delta s)^2 > 0$ in this expression. Here the four introduced components $\{\delta x^a; a = 0, 1, 2, 3\} \in \mathbb{R}^4$ and the 4×4 Lorentz metric $\eta = \mathrm{diag}(+1, -1, -1, -1)$ describe one of many intrinsic arithmetic substructures residing in the real continuum itself. Highlighting equation 2 amongst many other arithmetically possible homogeneous polynomial expressions for an infinitesimal real interval of time δs is a provisional assumption that we shall return to in section 5. The implicit possibility of this particular substructure at the infinitesimal level can be associated with any point of time as depicted in figure 3.

The important point here is that the *local* spatial geometry in figure 3 does not need to be *artificially appended* as an *independent* structure at each point in time, unlike the case for the spatial structures attached as 'fibres' to the base objects in figures 1 and 2. Rather the deployment of the particular substructure of time in equation 2, extracted through the defining arithmetic properties of the real continuum of equation 1 in the infinitesimal limit, *can itself provide* the local basis for a spatial form, as described in figure 3.

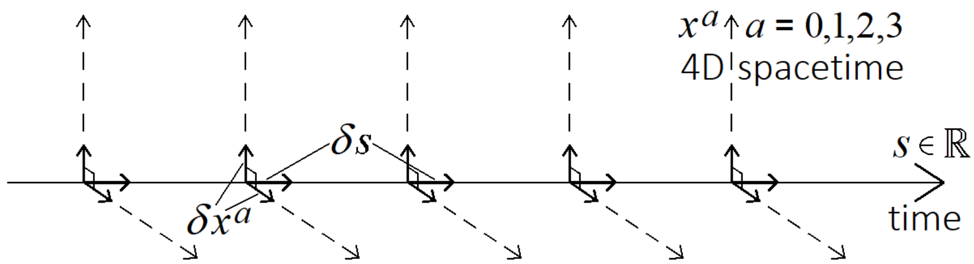

Figure 3: The intrinsic arithmetic substructure of equation 2 deployed to identify an infinitesimal 3-dimensional Euclidean spatial element $\{\delta x^1, \delta x^2, \delta x^3\}$, represented by the pairs of short arrowed lines at right-angles, associated with infinitesimal intervals of time δs. The full local 4-dimensional form of equation 2 provides the basis for an extended flat Minkowski spacetime, as indicated in part by the dashed arrowed lines.

Similarly as each interval $\delta s \in \mathbb{R}$ is embedded in the real line $s \in \mathbb{R}$ in figure 3 the local 4-dimensional *spacetime* form of equation 2 with $\{\delta x^0, \delta x^1, \delta x^2, \delta x^3\} \in \mathbb{R}^4$ is implicitly embedded within an arbitrarily extended 4-dimensional *spacetime* continuum with coordinates $\{x^0, x^1, x^2, x^3\} \in \mathbb{R}^4$ as partially represented by the dashed arrowed lines in figure 3. This translational symmetry (also depicted and described for the 3-dimensional case of $\{\delta x^1, \delta x^2, \delta x^3\}$ in [8] figure 1(a) and (b) for equation 2 therein) hence here applies for the four components on the right-hand side of equation 2 generating a 4-dimensional spacetime manifold with a global Lorentz metric structure inherited from the local metric of equation 2.

The result is similar to the situation in figure 2 for the global 3-dimensional spaces *attached* there except here with the four spacetime components $\{x^a\}$ intimately *linked* with the original base entity $s \in \mathbb{R}$ through equation 2 as described for figure 3. By comparison with figure 2 in this case the extended flat 4-dimensional Minkowski spacetime of special relativity is generated with an overall structure that is *not* a fibre bundle but rather describing a spacetime arena *lacking* any notion of absolute time (see for example [7] discussion of figure 17.13).

Here $s \in \mathbb{R}$ in figure 3 is no longer a universal time parameter in the resulting spacetime manifold since active global Lorentz transformations can be employed to boost to a different trajectory associated with a different time parameter that is equally permissible as a reference for events in the extended spacetime. Similarly the coordinate x^0 associated with δx^0 in equation 2 cannot provide a universal time parameter since passive Lorentz transformations in the Minkowski spacetime connect different global reference frames, each with its own set of inertial coordinates and each of an equivalent significance.

The parameter $s \in \mathbb{R}$ in figure 3 is known as 'proper time' since arbitrary intervals, as might for example be recorded by a clock, are invariant under active or passive Lorentz transformations. The temporal order of events along any worldline trajectory with a real proper time parameter s is also invariant and crucially the causal continuum properties of time are hence represented in this 4-dimensional spacetime structure with Lorentz symmetry properties inherited from equation 2. More generally, for events that are causally connected that ordered relation and the causal structure as a whole is preserved by Lorentz transformations, indeed with the Lorentz symmetry group itself following 'naturally from the single principle of causality' in Minkowski spacetime [9], as we discuss further in the following section.

Hence rather than having to append space to time, with the resulting Newtonian picture of figure 2, by exploiting the arithmetic substructure of the causal continuum of time in equation 2 a spatial structure *can be derived*, with a direct and explicit link with time, resulting in the special relativistic framework described above for figure 3. The construction of this latter manifold assumed the simplest translational symmetry in the extension from the elements of equation 2 to a full Minkowski spacetime arena. A more general means of building 4-dimensional spacetime from these local elements can however also be developed as we consider in the next section. A significant motivation for employing this basis in proper time is that it leads directly to a further generalisation from the 4-dimensional form of equation 2 that provides a basis for structures of matter, as a natural alternative to the approach of appending extra spatial dimensions such as in figure 1, as will then be described in section 4.

3 Construction of Spacetime: Contrast with a Causal Set

Given the creation of an extended 4-dimensional spacetime from the local structure of equation 2 the original flow of time $s \in \mathbb{R}$ of equation 1 uniformly occupies the full resulting spacetime volume, constructed as described for figure 3, without limit. This even flow of time through space is similar to that for the Newtonian picture of figure 2, except that the construction here via equation 2 and figure 3 leads to the spacetime of special relativity as described at the end of the previous section. However, for the universe with which we are familiar the curved 4-dimensional spacetime of general relativity will need to be described, requiring a more refined assessment of the augmentation from the local structure of equation 2 and the mutual relations between these elements in constructing an extended spacetime, as we consider in this section.

For the 13.8 billion year cosmic history of our universe an associated flow of time $s \in \mathbb{R}$ of equation 1, and as represented in figure 3, should not be thought of as a 13.8 billion year long 'one-dimensional line' *from* which the entire 3-dimensional spatial structure of the universe deriving from equation 2 'branches out sideways', and within which the original $s \in \mathbb{R}$ parameter occupies a privileged worldline location in spacetime. Indeed there is nothing in the universe we know of that corresponds to such a primary thread of time. A significant observation for the present theory is that the notion of a 'one-dimensional line of time' is a very limited concept, with rather the idea of an ordered causal progression expressing the essence of time, both in general and in the context of any extended 4-dimensional spacetime volume, as we shall elaborate further in section 6.

Hence rather than thinking of time as a 'one-dimensional line' we begin with a conception of *temporal progression*, with the principal emphasis on time as an ordered, causal continuum. As a mathematical entity this real continuum of equation 1 can be analysed at the level of infinitesimal intervals δs which, via the basic axiomatic properties of the real numbers $\mathbb{R}$, *have* an arithmetic substructure that *for example* can take the form of equation 2, representing a 'proper time' interval in being invariant under Lorentz transformations. As alluded to in the caption of figure 3 the quadratic form and rotation symmetry in the three components $\{\delta x^1, \delta x^2, \delta x^3\}$ matches the geometric form of a local Euclidean 3-dimensional *spatial* structure. Time itself can then be considered the *source* of the geometric structure of space and hence the progenitor *from* which the spacetime manifold of the universe can be constructed.

A significant factor in highlighting this particular arithmetic substructure for time, also noted at the end of the previous section, is that the proper time interval of equation 2 with Lorentz symmetry exhibits not only a 3-dimensional spatial form but also the crucial temporal property of *causality*, as we consider further here. Specifically, within this Lorentz metric signature convention, the four $\pm$ signs employed in equation 2 allow this expression to be interpreted as defining a local 4-dimensional 'light cone' structure, as pictured in figure 4, within which temporal causality is respected.

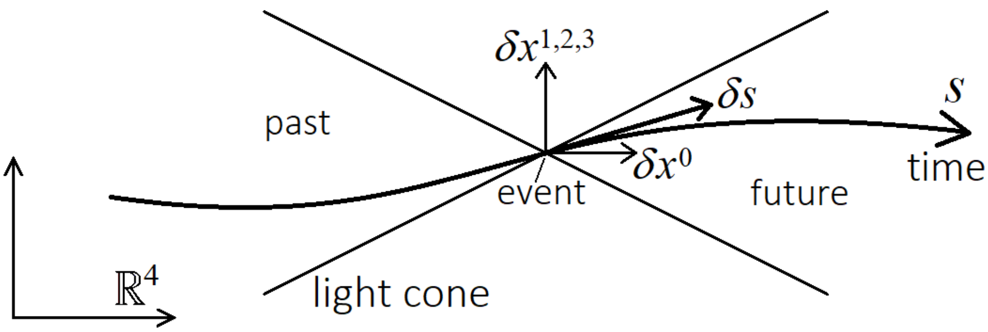

Figure 4: The arithmetic form $(\delta s)^2 = \eta_{ab}\delta x^a \delta x^b$ of equation 2 exhibits a geometric representation as a 'light cone' element of 4-dimensional spacetime on a patch of $\mathbb{R}^4$, as associated with a local substructure of time preserving the causality property – with future events to the right and past events to the left inside the light cone.

In taking the continuum $s \in \mathbb{R}$ the infinitesimal intervals $\delta s \to 0$ can arbitrarily closely approach a point-like *instant* in time. Similarly the elements of equation 2 with infinitesimal components $\{\delta x^a\}$ as sketched in figure 4 (not to scale) can be arbitrarily closely associated with an idealised point-like *event* in spacetime, now locally in $\mathbb{R}^4$. The light cone itself can here be considered to extend out further over a small but finite region of a local $\mathbb{R}^4$ coordinate patch.

Each point, with coordinates $\{\Delta x^0, \Delta x^1, \Delta x^2, \Delta x^3\}$ with respect to the origin at the central event in figure 4, *inside* the light cone corresponds to a small but generally finite 'timelike' interval with $(\Delta s)^2 = \eta_{ab}\Delta x^a \Delta x^b > 0$ and with $\Delta x^0 > 0$ for *future* events and $\Delta x^0 < 0$ for *past* events. In this manner the continuum of temporal causality can be represented in a local 4-dimensional spacetime form. Lorentz transformations preserve the order of such events and this causal structure, similarly as described at the end of the previous section with reference to [9], here applying at this local level (figure 4 describes the detailed structure of the local elements associated with each δs in figure 3). Hence the possible arithmetic substructure of time in equation 2 is *interpreted* as describing both the geometric *and* the causal structure of local elements of a 4-dimensional spacetime as depicted in figure 4, with these elements exhibiting the geometric properties of space while retaining the causal property of the flow of time from which they derive.

This local structure of 4-dimensional spacetime represents a *partial ordering* since the apparent temporal order of events *outside* the light cone, with 'spacelike' intervals $(\Delta s)^2 < 0$, is *not* in general preserved by Lorentz transformations, with in particular the notion of simultaneity for such events being dependent upon the choice of Lorentz frame. This property might be considered a 'side effect' of identifying a spatial structure from the local flow of time alone. That is, while we begin with the ordered progression of time as a real continuum as noted for equations 1 and 2, the resulting 4-dimensional spacetime geometry also necessarily incorporates events separated by spacetime intervals with $(\Delta s)^2 < 0$ that are not objectively ordered.

While the original intervals $\delta s \in \mathbb{R}$ can only 'fit together' in the continuum of $\mathbb{R}$, such as represented along the horizontal axis in figure 3, the arithmetic elements of equation 2 with components $\{\delta x^a\} \in \mathbb{R}^4$ can naturally be mutually related and 'fit together' in a more general way in the continuum of $\mathbb{R}^4$. Compared with the flat Minkowski case described for figure 3, building up an extended 4-dimensional spacetime from the local level in this way will lead to a more general 4-dimensional geometry on the global scale. If the light cones of two elements of equation 2 and figure 4 overlap in terms of local coordinate patches $\{x^a; a = 0, 1, 2, 3\} \in \mathbb{R}^4$ then, assuming a locally flat structure, whether the associated central events are directly *causally* connected or not can be readily determined, as pictured in figure 5.

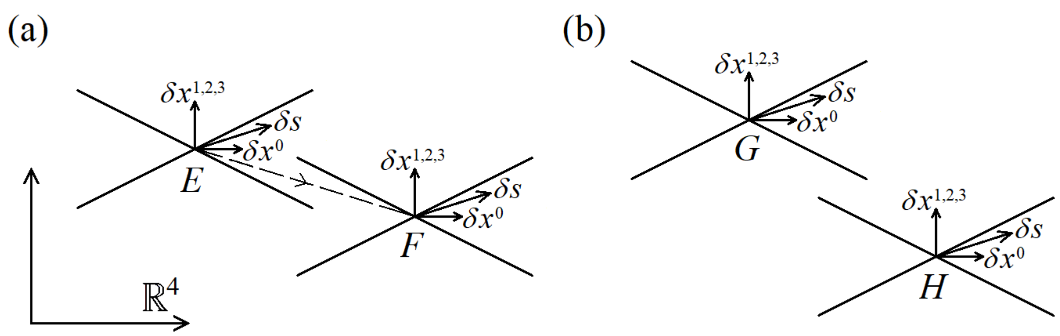

Figure 5: Two events corresponding to two elements in the form of equation 2 and figure 4 nearby in $\mathbb{R}^4$ may be (a) causally connected as indicated by the dashed arrowed line with event F in the future of event E or (b) not causally related if they are mutually outside the associated light cone structure as for events G and H.

In principle a Lorentz transformation could be applied to the $\{\delta x^a\}$ components of one element, before the juxtaposition with the other in $\mathbb{R}^4$, such that the trajectories of the two proper time intervals δs are aligned with respect to the local $\mathbb{R}^4$ coordinate patch as depicted for events E and F as well as G and H in figures 5(a) and (b); again assuming a local flatness and corresponding sense of parallelism. This is not necessary though since the spacetime constructed will in general accommodate a continuous family of such causal trajectories (as will be described for figure 7).

It is instructive to compare the above construction with a different and perhaps more familiar approach where an underlying structure of causality is key. The relations between events in figure 5 have some analogy with the elementary constructions in 'causal set theory', proposed as a possible approach to 'quantum gravity' [10, 11]. That approach is motivated in part on acknowledging 'the view that causality is a more fundamental organising principle, even than space and time, is an ancient tradition of thought' ([12] section 1) and by the ambition of 'pursuing the idea that spacetime *is* fundamentally its causal structure' ([13] section 2.1). The elementary conception there concerns the causality between momentary events with any material evolution, such as an apparent particle trajectory, considered as a pattern of such discrete events rather than as the mark of a substance enduring and extended through time. Any two events are causally related if it is possible to send a signal from one to another. In relativity, with the maximum signal speed being that of light, a complete description of the causal relations between events defines the causal structure of the universe.

A causal set is by definition a locally finite partially ordered set embodying the properties of both causality and discreteness [10, 11, 12, 13]. The nearest neighbours of a causal set are on the Planck scale [10, 13] with a Planckian density of discrete structureless elements that can be considered 'atoms of spacetime' by analogy with atoms of matter [12]. The spacetime atoms are linked by causal connections, as depicted in figure 6, to create a discrete 4-dimensional spacetime.

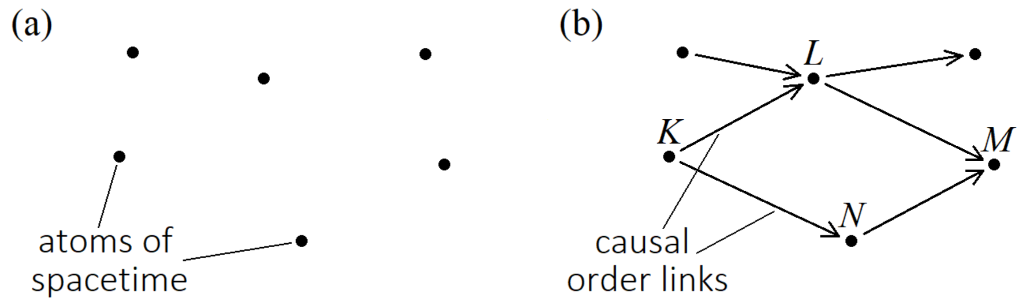

Figure 6: In causal set theory (a) 'atoms of spacetime', represented by the points, are (b) connected by causal relations, represented by the arrowed lines, to define a 4-dimensional spacetime structure. For example L is in the causal future of K whereas L and N are not causally related. While M is also in the causal future of K this is not explicitly shown as it is implied by the intermediate links via L or N. (Here time is directed from left-to-right rather than bottom-to-top, see for example [13] figure 3).

For the present theory the nearest equivalents of the atoms of spacetime in figure 6 are the temporal elements with $(\delta s)^2 = \eta_{ab}\delta x^a \delta x^b$ in figures 4 and 5. These elements of equation 2, interpreted as an arithmetic substructure of time, *themselves carry* and describe their mutual causal nature in the implied local 4-dimensional spacetime, without needing any additional assumptions or structure to make these links. That is, rather than having 'spacetime atoms' *and* 'causal links' as in figure 6 for causal set theory, here we have 'causal elements' of 4-dimensional spacetime incorporating their own explicit local spatial and causal relations in $\mathbb{R}^4$ as described for figure 5. These 'causal elements' could be considered 'atoms of time' in the sense that the infinitesimal intervals δs in equation 2 correspond to the 'smallest parts' of the continuum of time.

The causal set comparison was described above by way of a transitional analogy to help elucidate the construction of spacetime for the present theory. As a further significant distinction, rather than generating a structure with discrete atoms of spacetime here the meshing of the infinitesimal Lorentzian elements of equation 2 and figures 4 and 5 is taken to the continuum limit, resulting in a smooth extended spacetime not exhibiting any residual discrete or atomic properties on any scale. For the construction of this full extended continuous 4-dimensional spacetime, now in general with curvature, there will still be local inertial frames and spacetime coordinates at the local level with the structure of equation 2 and figure 4 with a local Lorentz metric η as consistent with the equivalence principle of general relativity. This justifies the local deployment of a light cone structure in the locally flat immediate vicinity of events as described for figure 4 and utilised for figure 5.

Through the extended construction of figures 5(a) and (b) involving a continuum of infinitesimal elements with $(\delta s)^2 = \eta_{ab}\delta x^a \delta x^b$ the causal progression property of time can hence be expressed through a global 4-dimensional spacetime manifold M_4 with everywhere local $\mathbb{R}^4$ coordinate patches $\{x^a\}$ accommodating a local Lorentz metric and light cone geometry. Having not introduced any additional structure beyond that implicit in the causal continuum of time alone through the arithmetic form of equation 2 the resulting manifold structure is here considered a 4-dimensional spacetime *realisation of* the flow of time itself. This extended structure is depicted in figure 7.

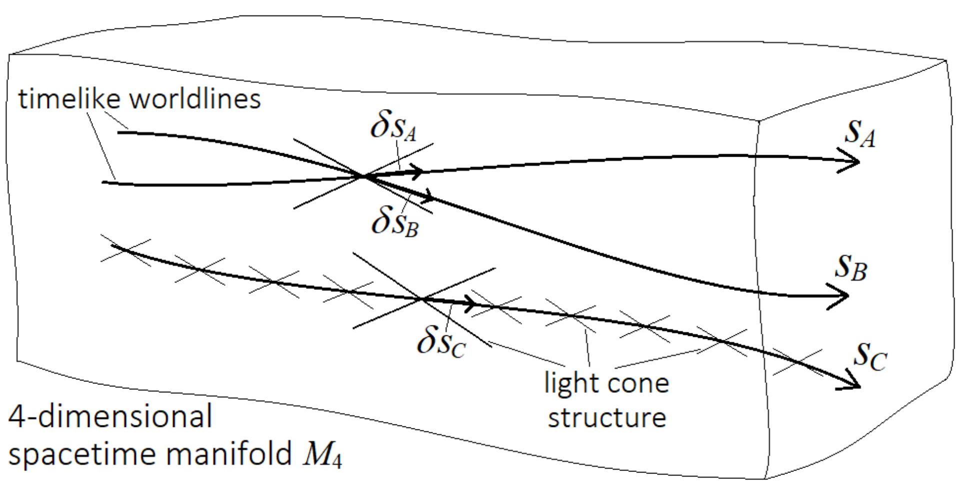

Figure 7: An extended, and in general curved, continuous 4-dimensional spacetime manifold M_4 constructed from elements of the local causal structure of time as expressed in equation 2 and figure 4. The manifold contains a continuum of timelike worldlines, such as denoted s_A, s_B and s_C, each of which is everywhere locally consistent with equation 2 in providing a local coordinate description of a local light cone geometry, such as accompanying the intervals δs_A, δs_B and δs_C and depicted along s_C.

The full extent of the global 4-dimensional spacetime volume, constructed via a continuous extension of the juxtaposition of elements described in figure 5, is profusely filled with causal proper time trajectories spanning arbitrary lengths of time, such as s_A, s_B and s_C depicted in figure 7. Throughout this multiplicity of worldline strands each such trajectory has everywhere the local substructure of equation 2, similarly as depicted for $s \in \mathbb{R}$ in figure 3 although now in general with varying orientation of the associated light cone geometry as for $s_C \in \mathbb{R}$ in figure 7, locally embodying this intrinsic arithmetic substructure of the causal progression in time *from* which the manifold itself is constructed.

Within the extended spacetime each local light cone element of figure 4 can be associated with a continuous range of local trajectories corresponding to intervals δs of equation 2 as represented in the resulting 4-dimensional spacetime, such as exemplified by δs_A and δs_B in figure 7. While considered equivalent in magnitude, $\delta s_A = \delta s_B$, each of these infinitesimal proper time intervals is manifested through the same local coordinates $\{x^0, x^1, x^2, x^3\} \in \mathbb{R}^4$ through the same expression of equation 2 but with different values for $\{\delta x^0, \delta x^1, \delta x^2, \delta x^3\}$ and correspondingly different local trajectories as related by a local active Lorentz transformation. This is similar to the case described at the end of section 2 for the construction of a flat Minkowski spacetime through the simplest extension from equation 2 globally into $\mathbb{R}^4$ as pictured in figure 3, there with global active Lorentz transformations mapping between choices of a global time parameter s in the 4-dimensional spacetime of special relativity. This now applies at the local level for invariant intervals δs by the local flatness in figure 7.

Hence worldline strands that intersect locally as for δs_A and δs_B in figure 7 will at such points be related by local active Lorentz transformations, and the corresponding mutual physical time dilation effects, while leaving the local light cone and coordinate patch $\{x^a\} \in \mathbb{R}^4$ structure untouched in this locally flat spacetime of special relativity with the local Lorentz metric η_{ab} of equation 2. Similarly passive local Lorentz transformations between such local inertial coordinate frames also leave the local light cone geometry and causal structure of the manifold M_4 invariant.

On the other hand in general global coordinates $\{x^\mu\} \in \mathbb{R}^4$ a more general symmetric metric $g_{\mu\nu}(x)$, with indices $\mu, \nu = 0, 1, 2, 3$, as a function of location $x \in M_4$ will describe the extended geometry (see for example [1] section 3.3 for a review of the corresponding structures of Riemannian geometry involved). A local proper time interval can be expressed as $(\delta s)^2 = g_{\mu\nu}(x)\delta x^\mu \delta x^\nu$ in a manner invariant under general coordinate transformations, with no preferred sets of global coordinates in general. Any two intervals at different 4-dimensional locations, such as δs_A and δs_C in figure 7, will be mutually related according to this extended metric structure in the curved spacetime as consistent with the relative time dilation effects in the geometric framework of general relativity (see discussion of 'twins A and B' in [1] section 5.3 ending). Hence, while *constructed* from elements of the causal continuum of time alone, there is certainly no universal global time parameter for this extended manifold.

The manifold M_4 is a consistent manifestation of the causal continuum of time in that it contains throughout objectively fully ordered strands, such as the timelike worldlines s_A, s_B and s_C in figure 7, each connecting unambiguously ordered events. The full extended structure in figure 7 represents a partial ordering in time as many locations in the spacetime, such as the events associated with δs_A and δs_C, are not temporally ordered in an absolute sense. This corresponds to the lack of an objective notion of simultaneity for spacelike separated events in relativity, which is dependent upon the choice of reference frame. Here the partial ordering might be considered an inevitable consequence of expressing the causal continuum of time in an extended spatial form, with this 'side effect' also described at the local level in the discussion after figure 4. However, all events throughout the spacetime transpire in a fully ordered consistent manner from any one perspective, fully preserving this property of time from any given subjective point of view. Hence while globally there is no fixed temporal order, or objective property of simultaneity, for events that cannot be connected by a worldline within or on a possible sequence of connecting light cones, an unambiguous chronological history of all events can still be defined with respect to any physically propagating perspective.

For the 4-dimensional spacetime of our own universe of the many possible timelike worldlines, such as s_A, s_B and s_C in figure 7, some will be associated with the trajectory of physical objects such as clocks, and some with observers such as any one of ourselves. An observer following s_A for example would see the extended universe, as constructed from elements of equation 2 as described in this section, from *that* perspective. Indeed any physical observer will necessarily be *threaded* through a causal sequence of light cones, locally mutually linked as described for figure 5(a), as effectively 'pinched' into an extended but relatively localised 3-dimensional spatial region. This is necessary in order to describe a causally coherent physical entity, as presumably required for the temporal development of any such thinking and reasoning individual observer. The overall temporal progression of such a comparatively localised spatial entity might then be approximately associated with an idealised worldline such as s_A, s_B or s_C in figure 7.

The link between causality and the structure of spacetime, with the former determining to a considerable degree the properties of the latter, is well established (see for example [9, 14, 15, 16, 17, 18, 19]). The crucial additional observation here is that in starting with *time* as the ordered real continuum in equation 1 the elementary arithmetic substructure implicit in the real number system can be exploited to generate the continuum of *space* itself via the elements of equation 2, as we have elaborated for figures 4, 5 and 7. In this section we have hence described how the causal continuum of time can be directly represented in an extended 4-dimensional spacetime form through the inherent substructure of infinitesimal intervals of time in equation 2.

However, so far we have not described how the source for a matter content, as needed for example to support the clocks and observers discussed above, might be incorporated. In the following section we describe how the construction of spacetime *from* the flow of time alone leads to a natural arithmetic generalisation from the local form of equation 2 that *directly* generates a structure of matter in the external 4-dimensional spacetime and review the physical consequences. The inevitability of this local generalisation, and the resulting physical structures, is one of the main advantages of adopting this approach. Given the possibility of this generalised form for a proper time interval, in section 5 we shall then return to consider further the reasons behind the prominence of the intermediate form for proper time of equation 2 that is central to the construction of the extended spacetime arena.

4 Matter in Spacetime from Generalised Proper Time

In the previous section we described how the flow of time $s \in \mathbb{R}$ of equation 1 arithmetically contains the intrinsic infinitesimal substructure of equation 2 through which progression in *time* can be realised as a causal flow through a 3-dimensional *space* with the local light cone structure of an extended 4-dimensional spacetime as described for figure 7. With space deriving from, and inextricably linked with, time this implies a relativistic picture of a spacetime manifold with the local Lorentz symmetry properties of equation 2.

While the extended spacetime constructed as described for figure 7 can be curved the nature of the curvature as well as a source for matter, and the relation between these two structures, still requires an explanation. This 4-dimensional framework might then begin to sound like we are simply describing what we already know about the spacetime of general relativity. However, here with the initial focus on time on the *left-hand side* of equation 2 the construction of the local geometry and corresponding extended manifold from a form *for* proper time intervals described in the previous section naturally lends itself to further generalisation that *does* yield a rich vein of novel explanatory power as we describe in this section.

By comparison with standard approaches matter fields *could* be added by hand to the 4-dimensional spacetime of figure 7 as a background manifold M_4 and equations of motion pragmatically introduced, for example through a Lagrangian method, as for many phenomenological models (such as the Standard Model of particle physics itself [20]). These structures could be introduced via the inertial coordinate frames of the locally flat spacetime regions using the equivalence principle ([1] section 3.4). More in the spirit of the present paper, and with space being a continuum, infinitesimal real intervals $\delta r \in \mathbb{R}$ of the space dimensions in figure 7 could be decomposed into an arithmetic substructure, similarly as for the intervals $\delta s \in \mathbb{R}$ of the continuum of time of equation 1 via equation 2, now as a potential source of matter.

However, in this theory space *itself*, and all spatial components, derive *from* time as *the* fundamental entity *through* equation 2 and it is hence *this* expression for infinitesimal proper time intervals $\delta s \in \mathbb{R}$ that can be generalised further, in turn naturally introducing additional components that can be interpreted as the source for a structure of matter over and above the local 4-dimensional spacetime geometry. Hence it is not necessary to artificially append *new* structures, as for introducing matter fields by hand or appending extra spatial dimensions – on the contrary here there is no compelling argument as to why equation 2 should *not* be arithmetically generalised as permitted by the innate structure of the real numbers representing the continuum of time and the consequences explored.

At a purely local level models based on extra spatial dimensions append further quadratic terms to equation 2 with an augmented Lorentz metric form as discussed following figure 1. That could be considered a limited special case of the generalisation of a local proper time interval to be introduced here, yielding correspondingly limited forms of matter fields from a direct analysis. In other approaches to constructing 4-dimensional spacetime from a local level, such as causal set theory, there is no natural generalisation, such as beyond the construction of figure 6, to provide direct links with matter, let alone with the specific physical structures empirically observed. While a form of matter might be hidden in such a theory, living in relations of the causal set dynamics [21], more typically the causal set is coupled to matter fields by explicitly attaching field values to the discrete structureless atoms of spacetime to describe matter degrees of freedom [22].

The present theory then has this significant advantage over other approaches in beginning with time in equation 1 in that through a further direct generalisation from equation 2 it can reach beyond the basic local spacetime structure of general relativity constructed in figures 4 and 5 and underlying figure 7. That is, from an arithmetic point of view there is no requirement to limit the intrinsic substructure of an interval of the continuum of time to either a 4-dimensional or a *quadratic* form as for equation 2. Rather we can consider the generalisation of infinitesimal intervals δs to the general form for proper time:

$$(\delta s)^p \; = \; \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots \tag{3}$$

Here p is the power of a homogeneous polynomial in n infinitesimal components $\{\delta x^a\}$ with each index $a, b, c, \ldots = 0, \ldots, n-1$. With each coefficient $\alpha_{abc\ldots} = -1, 0$ or $+1$ having p indices this form is a direct generalisation from equation 2 and the Lorentz metric $\eta = \text{diag}(+1, -1, -1, -1)$ with each 2-index component $\eta_{ab} = -1, 0$ or $+1$.

Further, as a generalisation from the Lorentz group a full symmetry $\hat{G}$ acts upon the $\{\delta x^a\} \in \mathbb{R}^n$ components on the right-hand side of equation 3 leaving invariant the interval δs, which is hence still considered 'proper time', now expressed in this generalised form. This general equation then *contains* the right-hand side of equation 2 as a quadratic *substructure*, and hence can be written as:

$$(\delta s)^p \; = \; \left[\eta_{ab}\delta x^a \delta x^b\right] (\delta x^4, \ldots, \delta x^{n-1})^{p-2} \; + \; (\delta x^0, \ldots, \delta x^{n-1})^p \tag{4}$$

With $a, b = 0, 1, 2, 3$ in the first term the 4-component spacetime form of equation 2 is explicitly embedded. Through this 4-dimensional factor the causal continuum of time can be expressed in an external geometric spacetime form similarly as described for figure 7 in the previous section. In this first term the factor $(\delta x^4, \ldots, \delta x^{n-1})^{p-2}$ is a $(p-2)^{\text{th}}$-order polynomial in the remaining $(n-4)$ components, while the second term $(\delta x^0, \ldots, \delta x^{n-1})^p$ represents the further contributions, in all components, to the full p^{th}-order homogeneous polynomial of equation 3.

While the four components $\{\delta x^a; a = 0, 1, 2, 3\}$ hence map onto the basis for the local external 4-dimensional light cone structure, the additional $\{\delta x^a; a \geq 4\}$ components in equation 4 are interpreted as the basis for matter fields, as underlying all physical and empirical structures *in* the extended spacetime of figure 7. Hence this simple generalisation to the form for infinitesimal intervals of proper time in equation 3, which might be considered to represent 'generalised atoms of time', has a substructure that incorporates *both* the local 'infinitesimal elements' of 4-dimensional spacetime, similarly as described for equation 2 and in figures 4, 5 and 7, *as well as* the elementary 'building blocks' of matter, in both cases deriving from the continuum of the flow of time. This highly unifying picture has been achieved on *dropping* the assumption of a quadratic structure in generalising proper *time* from equation 2 to equation 3, which is freely permitted since the aim is to account for a structure of *matter*, rather than more components of *space*.

The larger symmetry $\hat{G}$ for a specific form of equation 3 is necessarily broken in identifying the local external spacetime geometry through the extraction of the 4-dimensional Lorentzian substructure of equation 2 and figure 4 via equation 4, with a surviving subgroup symmetry:

$$\text{Lorentz} \times G \, \subset \, \hat{G} \tag{5}$$

Alongside the external Lorentz symmetry this leaves an internal symmetry G as a residual subgroup of $\hat{G}$, as well as the fragmented $\{\delta x^a\}$ components transforming under the broken symmetry and forming a multiplet structure, as a basis for structures of matter. Given this generalisation to equation 3 and the symmetry breaking entailed in extracting a 4-dimensional spacetime arena M_4 this manifold, as originally introduced in figure 7, now effectively acts as the base space of a fibre bundle structure with the residual components residing in the fibre space providing the basis for matter fields, in a manner analogous to the structure of figure 1 [8]. The necessity of identifying the preferred set of four components as the basis for the local external spacetime, from the n-component form of equation 3, implies the *absolute* symmetry breaking down to equation 5, with independent external and internal symmetry factors, as the basis for *all physics* in spacetime.

In terms of a natural mathematical augmentation the direct generalisation from the 4-component quadratic form with Lorentz symmetry in equation 2, to explicit expressions for equation 3 with a high degree of symmetry, leads to a unique series of structures including a 27-component cubic form with a $\hat{G} = \mathrm{E}_6$ symmetry and a 56-component quartic form with a $\hat{G} = \mathrm{E}_7$ symmetry ([23] equations 52 and 63 respectively, [24] table 2, expressed with equation 3 rewritten in the form of equation 10 in section 8 here). This hence makes a direct connection with structures of the exceptional Lie groups in principle including also $\hat{G} = \mathrm{E}_8$ as the largest of these, as well as with the octonions as the largest division algebra, as mathematical structures known to be of interest in unification models ([23] subsection 2.1, [24] section 1).

Significantly, the transformation properties of the fragmented components from the right-hand side of equation 4 under the broken symmetry of equation 5, as analysed explicitly through to the $\hat{G} = \mathrm{E}_7$ case, are indeed found to closely resemble features of the multiplet structure of one generation of leptons and quarks in the Standard Model. These features include an internal $G = \mathrm{SU}(3)_c \times \mathrm{U}(1)_Q \subset \mathrm{E}_7$ symmetry with the set of $\{\delta x^a\} \in \mathbb{R}^{56}$ components including fragments transforming under the colour $\mathrm{SU}(3)_c$ as singlets and triplets with an appropriate fractional charge structure under the electromagnetic $\mathrm{U}(1)_Q$ symmetry. Elements of electroweak theory and symmetry breaking are also identified, including a left-right asymmetry with respect to spinor structures obtained under the external Lorentz $\subset \mathrm{E}_7$ symmetry (see [23] figure 4, [24] tables 1 and 3, and discussion therein).

In models based on extra spatial dimensions a considerable amount of further structure has to be postulated or contrived in order to make any connections with the Standard Model. Here dropping the quadratic assumption, and allowing for $p > 2$ in equation 3, leads directly to unique mathematical structures and a necessary symmetry breaking through equations 4 and 5 as described above. The resulting non-trivial connections between the present theory and the empirical structures of the Standard Model are then derived here *directly* from the elementary structure of generalised proper time, *without* needing to introduce the required features by hand to model the observations.

The detailed analysis that has been performed for the E_6 and E_7 levels leads to the proposal of a further augmentation for an E_8 level. There remains an open question concerning the explicit form equation 3 with a $\hat{G} = \mathrm{E}_8$ symmetry might take and the precise role of the octonion algebra, which is anticipated to be central to this construction (as discussed for [23] equation 74 and [24] equation 9). Taking into account basic properties of the Lie group E_8 this predicted form for equation 3 in this sector can, however, be provisionally written as:

$$(\delta s)^8 = Q(\{\delta x^a\}) \quad \text{with} \quad \mathrm{E}_8(\mathbb{O}) \quad \text{acting on} \quad \{\delta x^a\} \in \mathbb{R}^{248} \tag{6}$$

Here Q represents a homogeneous polynomial form, potentially of octic order, in 248 components $\{\delta x^a\}$ with an octonion-rich composition and E_8-type symmetry. Known mathematical constraints on such a possibility suggest that this proposed ultimate form for proper time might have the capacity to both complete the Standard Model multiplet structure for a full three generations ([23] section 5, [24] section 3) and also determine novel empirical predictions. In particular new physics is strongly indicated in the Higgs and neutrino sectors, with the Higgs likely to be a composite state and effectively embedded in the right-handed neutrino sector ([25] section 4, [26]).

As well as new physics extending the Standard Model as deriving from the above chain of exceptional Lie group symmetries of unique $p > 2$ expressions for equation 3, the general nature of this expression for proper time implies the possibility of alternative explicit forms that can provide natural candidates for the dark sector (as initially proposed for [25] equation 42 and explored in detail in [27]). Indeed the original $(n > 4)$-dimensional quadratic $p = 2$ 'spacetime' extension from equation 2, as discussed below figure 1, to the form ([27] equations 12 and 13):

$$(\delta s)^2 = \hat{\eta}_{ab}\delta x^a \delta x^b \tag{7}$$

with $n \times n$ Lorentz metric $\hat{\eta} = (+1, -1, \ldots, -1)$ and $a, b = 1, \ldots, n-1$ itself describes a possible branch for generalised proper time. The breaking of the full $\hat{G} = \mathrm{SO}^+(1, n-1)$ symmetry of equation 7, in the manner described for equation 5, yields a hidden internal $G = \mathrm{SO}(n-4)$ gauge symmetry, acting on a set of $(n-4)$ scalar components $\{\delta x^a; a = 4, \ldots, n-1\}$ ([27] table 2), that can be interpreted as the basis for a 'dark QCD' sector with very suitable properties for dark matter ([27] sections 5 and 6).

There is also a further $p > 2$ sector for equation 3 with ([27] equation 20):

$$(\delta s)^p = \det(\{\delta x^a\}) \quad \text{and} \quad \{\delta x^a\} \in \mathrm{h}_p\mathbb{C} \tag{8}$$

Here the $n = p^2$ components $\{\delta x^a\}$ are embedded in $p \times p$ Hermitian complex matrices $\mathrm{h}_p\mathbb{C}$, upon which a full $\hat{G} = \mathrm{SL}(p, \mathbb{C})$ symmetry acts leaving the proper time interval δs invariant. In this branch, for $p \geq 4$, the symmetry breaking results in an internal $\mathrm{SL}(p-2, \mathbb{C})$ symmetry factor, that is a non-compact gauge group. Such a non-compact internal symmetry in general implies an associated Lagrangian term that will generate a source of *negative* kinetic energy, which might be considered problematic or non-physical. However, a source of negative kinetic energy is a key ingredient in 'phantom dark energy' models, with equation 8 hence generating a potential contribution to the observed accelerating expansion of the universe ([27] section 7).

Collectively the three branches of equations 6, 7 and 8 might then provide a complete description of the 'cosmological pie chart', with the universe presently composed of 5% ordinary Standard Model matter, 26% dark matter and 69% dark energy [28]. Given the radically different empirical properties of these sectors of matter in the universe it is striking that in principle they can all derive from 'one simple equation' in the general form of equation 3. Further, this expression for generalised proper time is well-motivated from an elementary conceptual level, and has not been contrived or invented as might be the case for example for a specific Lagrangian structure. While addressing the puzzle of how three very different forms of matter can have a common origin, models of dark QCD and phantom dark energy are also each associated with an argument to account for the apparent coincidence of the three energy densities, which are within an order of magnitude or so of each other as observed at the present cosmological epoch ([27] sections 2.1 and 7 and references therein).

These three different explicit forms that equation 3 can take, as described above for equations 6, 7 and 8, and their associated structures of matter, are gravitationally linked through the common 4-dimensional spacetime root of equation 2 as embedded in equation 4 (see the discussion of [27] figure 1 and equation 19, and also below). With gravity being a rather blunt instrument through which to study the empirical microscopic form of the dark sector a well-motivated fundamental theory, such as described here for generalised proper time, will be needed if ever there is to be a full understanding of these novel invisible forms of matter.

If the possible generalised forms for proper time terminated in equation 2 the most direct continuation from the geometric basis in figure 4 to an extended manifold as discussed for figure 7 would generate a flat 4-dimensional Minkowski spacetime, essentially as described for figure 3. Similarly there would be no extra components as a basis for matter fields and hence the manifold would correspond to the empty spacetime arena of special relativity. In general however from a full ($n > 4$)-component form for equation 3, such as the visible matter sector of equation 6, there may be many ways to project out a 4-component fragment in the form of the right-hand side of equation 2, via equation 4, corresponding to the local spacetime structure depicted in figure 4. Such 4-dimensional substructures with matching components can still be contiguously stitched together in the $\delta s \to 0$ continuum limit similarly as described for figure 5 to generate a smooth and continuous spacetime structure as depicted in figure 7. Again this manifold has a local light cone structure and is consistent with the local flatness of the equivalence principle, but now with an explicit *source* for the curvature of the extended spacetime manifold as may be associated with components of *matter*.

In particular the 4-dimensional fragments, projected out of equation 3 and into the local external spacetime structure, have a norm from the right-hand side of equation 2 that can now vary in magnitude thus directly inducing localised geometric warping effects. Through the Einstein field equation, discussed below for equation 9, this spacetime warping can be associated with the 'origin of mass' and in turn with the role of the Higgs field in the Standard Model (see for example discussion of [25] equations 22–24 and [29] equations 41–42). The geometry of the external 4-dimensional spacetime manifold will also depend upon the internal gauge field structure, as associated with the internal symmetry G of equation 5, in a manner analogous to the construction of non-Abelian Kaluza-Klein theories ([8] in particular equation 93).

The curvature of the spacetime is hence directly related to the structure of fields on M_4 deriving from the internal symmetry G and the n components $\{\delta x^a\}$ of equation 3, in relation to the local external 4-dimensional $\{a = 0, 1, 2, 3\}$ spacetime fragments, and as associated with the apparent matter field composition. For this more general case the Lorentz metric η_{ab} of equation 2 will still apply in a suitable limit of local coordinates while a more general metric $g_{\mu\nu}(x)$, with $\mu, \nu = 0, 1, 2, 3$, as a function of $x \in M_4$ in a choice of global coordinates $\{x^\mu\} \in \mathbb{R}^4$ will describe the extended geometry as noted for figure 7. In constructing possible solutions for identifying a spacetime manifold M_4 through generalised forms of proper time in this way the Einstein tensor $G^{\mu\nu}(x)$, as a standard geometric construction in the derivatives of the metric $g_{\mu\nu}(x)$ (again see for example [1] section 3.3), can then be expressed in general coordinates as (with $a = 0,..., n-1$):

$$G^{\mu\nu} \; = \; f^{\mu\nu}(A(x), \{\delta x^a\}) \; =: \; -\kappa T^{\mu\nu} \tag{9}$$

The tensor function $f^{\mu\nu}$ depends upon the structures deriving from the absolute breaking of the full symmetry $\hat{G}$ in equation 5 as associated with the local projections out of equation 3 required to identify the spacetime manifold M_4 with a local external Lorentz $\subset \hat{G}$ symmetry. These structures include gauge fields $A(x)$ associated with the residual internal symmetry $G \subset \hat{G}$ and the fragmented components $\{\delta x^a\} \in \mathbb{R}^n$ of equation 4 transforming under this broken symmetry (see for example [29] equations 33 and 34, based on the notation of equation 10 in section 8 here, and [29] equations 40 and 42 for explicit forms of the above expression).

The construction in equation 9 *defines* the energy-momentum tensor $T^{\mu\nu}(x)$ of the corresponding matter fields in a manner fully consistent with the Einstein field equation $G^{\mu\nu} = -\kappa T^{\mu\nu}$, with $-\kappa$ the usual normalisation constant ([1] equation 3.75). Hence in this theory both the 4-dimensional spacetime M_4 as well as the matter it contains derive from generalised proper time in a manner incorporating the Einstein field equation for a curved spacetime with a local geometry consistent with the equivalence principle. This framework is hence compatible with the formalism of general relativity while also reaching beyond to determine explicit forms of matter. As reviewed above for equations 6, 7 and 8 these forms of matter may describe both the Standard Model and the dark sector, in principle accounting for the full evolutionary history of the universe as depicted in figure 8.

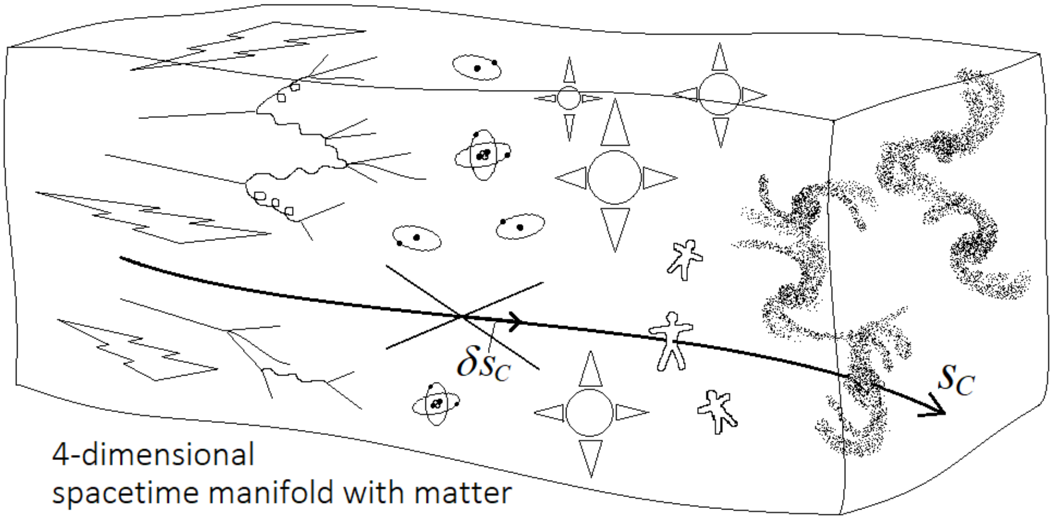

Figure 8: Construction of the entire universe in an extended 4-dimensional spacetime manifold M_4 preserving the causality structure of figure 7 now via the local form of equation 2 subsumed within elements of the general form for proper time of equation 3; the residual fragmented components provide the source for curvature and the structure of matter through equation 9 from the scale of elementary particle and laboratory phenomena to the full evolutionary history of galactic and cosmological formations.

The underlying simplicity of the theory as a unification based on forms of time alone inevitably implies significant constraints on the structure of matter as emerging from the Big Bang and as investigated in the present day laboratory. These constraints, associated with equations 3 and 9, lead to the laws of physics and equations of motion for matter fields, without the need for example to postulate a Lagrangian function and technique (as described for [29] equations 36–45 and the associated references therein). As an example of such a physical structure Maxwell's equations for the electromagnetic field can be derived from equation 9 for the case of an internal U(1) gauge group obtained from the symmetry breaking of equation 5 ([29] equations 45–47, see also [8] figure 3(b) for such an example as underlying the general principal fibre bundle construction of [8] figure 5). The corresponding physical solutions include the case of an electromagnetic wave propagating at the speed of light ([29] equations 48–52), and hence transmitting causal signals *on* the light cone of figure 4 (with such a light cone exemplified in association with δs_C in figure 8).

Historically the constancy of the speed of light in all reference frames, propagating between events with an invariant proper time interval $\Delta s = 0$, provided a central postulate for special relativity and implied the Lorentz transformations – which then in turn also apply for arbitrary non-zero 4-dimensional intervals in spacetime leaving any value $(\Delta s)^2 \neq 0$ invariant. By contrast here the theory originates from the mathematical basis of non-zero but infinitesimal real proper time intervals $\delta s \neq 0$ in equations 2 and 3. Here the Lorentz symmetry of equation 2 (or of the corresponding local 4-dimensional spacetime fragment extracted in equation 4) for $(\delta s)^2 > 0$, as represented in the local geometry of an extended spacetime, in turn also applies for all physical phenomena derived including entities propagating at the speed of light with 4-dimensional interval $\delta s = 0$. That this corresponds to a fixed maximum speed for causal signal propagation, as exemplified by phenomena such as light and gravity waves, that is the same in all reference frames is then a *conclusion* rather than a starting *postulate* (see also [30] page 4 discussion). This is the case since for any greater speed $(\delta s)^2 < 0$ in 4-dimensional spacetime, corresponding to a spacelike interval outside the light cone which, while still invariant, connects non-causally related events with a frame-dependent temporal order.

The local generalisation of proper time from the 4-dimensional spacetime form of equation 2 to the n-dimensional form of equation 3, and the resulting symmetry breaking, leads directly to the detailed local symmetry and multiplet structures of matter as empirically observed, *without* the need to posit specific fields or particle states to describe these properties. Similarly, the aim for this unified theory is to *derive* the observed quantum properties of particle entities without needing to impose any postulates of quantum mechanics or quantum field theory. That is, here the basis for unification is through equation 3 for generalised proper time, rather than through any insistence that 'everything is quantum', implying for example that there is no compelling need to 'quantise' gravity.

With many possible solutions for equation 9 to identify an extended continuous 4-dimensional spacetime, as deriving from components of generalised proper time here considered for the visible Standard Model sector of equation 6, local degeneracies in the apparent matter field composition, associated with the same physical geometry of a localised spacetime region, imply an intrinsic indeterminacy in the behaviour of matter as observed in 3-dimensional space evolving with respect to a timelike coordinate. Such inherent uncertainty is a characteristic feature of quantum phenomena. While classical probabilities are associated with the 'number of ways' things can *happen in* spacetime, here quantum probabilities are associated with the 'number of ways' for *building* the extended 4-dimensional spacetime itself through equation 9. More generally quantum theory as applying for all *non*-gravitational fields is proposed to derive as a limiting approximation of the candidate for 'quantum gravity' that can be constructed within this framework ([29], [1] chapter 11).

Explicit connections with a standard formalism for quantum field theory calculations for particle physics experiments can be identified in the limit of an approximately flat extended spacetime environment in which a linearised form of general relativity can be adopted ([29] section 5). A central aim is to relate probabilities based on a 'number of ways' local field composition degeneracy count, underlying the construction of a given local spacetime geometry, with the corresponding standard calculations in quantum field theory as based on unitary evolution and complex transition amplitudes ([29] equation 70). Consistency with the Coleman-Mandula theorem in quantum field theory is assured by the *absolute* breaking of the full symmetry $\hat{G}$ for all physics in spacetime that was noted for equation 5 (as also described for [29] equation 92). While gravity itself is *not* quantised and the external spacetime is completely continuous and smooth, as for general relativity, discrete matter effects, including elementary particle quanta, can be identified as a consequence of the constraints implied in constructing an extended 4-dimensional spacetime together with a matter composition essentially from the flow of time alone through equations 3 and 9 ([29] section 6).

Hence Standard Model particle multiplets and physical particle states as well as other physical structures including the quantum and atomic properties of matter generally can in principle arise in this framework in a fully coherent manner together with a general relativistic description of gravity. Through the generalisation of proper time from equation 2 to 3 all forms and properties of a matter content are filled out in the extended spacetime of figure 7, including also for the dark sector as described for the branches of equations 7 and 8, as directly related to the spacetime curvature on all scales through equation 9 and as collectively represented in figure 8.

The timelike worldlines profusely traversing the 4-dimensional spacetime arena as described for figure 7 still apply as represented by s_C in figure 8, with some such trajectories now associated with observers or galaxies in the universe. As a special case, given the high degree of symmetry on the large scale for our universe, a worldline such as s_C attached to an idealised galaxy could be associated with 'cosmic time' t. While cosmic time, beginning at $t = 0$ in the Big Bang, has recorded 13.8 billion years through to the present day the underlying time parameter as represented by s_C scales differently in the extremely early universe. In particular within the first small fraction of a second of the Big Bang, before material properties stabilise over the projection of the local structure of 4-dimensional spacetime from equation 3, as $t \to 0$ it is possible for $s_C \to -\infty$. The relation between a cosmic time parameter t and the fundamental flow of time s, as well as the potential implications for any 'pre-Big Bang' era, is discussed for ([1] figures 13.4 and 13.5).

The possible connection with phantom dark energy models, described for equation 8, suggests that the evolution of the universe may terminate after a finite period of cosmic time in a 'Big Rip' ([27] section 7, [31]). This would then present a rather symmetric picture of the complete history of the universe. The 'initial singularity' of the

Big Bang at the origin of cosmic time corresponds to a limit of infinite energy density in ordinary and dark matter – followed by a period of structure formation including the first nuclei, atoms, galaxies, stars and planets. In the future as the ever increasing density of phantom dark energy eventually starts to overcome all other forces the reverse situation would arise – with galaxies torn apart, planets and stars exploding and finally atoms and even nuclei ripped apart just before the 'ultimate singularity' of infinite phantom dark energy density is reached. Potentially the worldline parameter in figure 8, representing the underlying flow of time s, would progress as $s_C \to +\infty$ on approaching the finite age in cosmic time t marking the 'Big Rip', mirroring the situation described above for the Big Bang.

However, in order to understand the nature of what actually physically transpires for such 'infinite energy density singularities' a full working out of this quantum gravity framework will be required. This will include an understanding of the exact role of internal non-compact gauge groups, such as arising from the symmetry breaking of equation 8, and the corresponding physical consequences in constructing the external 4-dimensional spacetime and $G^{\mu\nu}(x)$ through equation 9. The interpretation of such contributions from non-compact gauge groups in terms of energy-momentum $T^{\mu\nu}(x)$ might then in turn be indirectly deduced from the right-hand side of that equation. Whether this contribution could indeed be considered as a source of 'negative kinetic energy', and the degree to which it may be related to dark energy models, phantom or otherwise, might then be assessed.

We end this section with a brief summary of the main points presented. While locally incorporating the equivalence principle building a physical theory in an extended 4-dimensional spacetime from the local spacetime structure identified within the infinitesimal form for generalised proper time of equation 3 leads to the framework of a curved spacetime. This structure is consistent with general relativity with the addition of an explicit matter composition exhibiting the characteristic properties of quantum phenomena as briefly reviewed with reference to equation 9. Full connections with the familiar mathematical formalisms of quantum field theory and quantum mechanics are proposed to arise in the appropriate spacetime limits of this quantum gravity framework. The matter derived exhibits further appropriate features matching the observed empirical world. These include highly non-trivial connections with the Standard Model of particle physics, culminating in the prediction of the form described for equation 6 and pointing to areas of new physics beyond, with the further explicit branches of generalised proper time of equations 7 and 8 available to accommodate the dark matter and dark energy sectors respectively.

With all matter in *space*-time here hence deriving from the flow of *time* itself, as represented in figure 8, the fundamental origin of all the constraints and the resulting physics essentially arises from the minimal requirement of a framework of *time and space* as the basis for an empirical world. That is time and space can both be considered necessary structures through which a universe must be constructed for it to be observed at all, as we discuss in the following section.

5 A Universe Shaped through Forms of Time and Space

From an objective point of view everything that *happens* in the universe *happens* in time. The flow of time has the property of 'an æthereal medium pervading all bodies' ([32] section 1 opening) which, unlike the postulated 'luminiferous ether' of Maxwell, is a very familiar entity. All successful physical theories, from Newtonian mechanics and Maxwell's electromagnetism to relativity and quantum theory, incorporate a continuous time parameter to mark the chronological occurrence of events and processes. From a subjective point of view it is also evident that all of our observations in the world take place through the course of an *experienced* flow of time. More generally it is difficult to conceive of any subjective thoughts, experiences or perceptions that do not involve a sense of time or change. As a variation on a well-known philosophical quote Descartes *could* have said 'I think therefore time exists'.

It is this universal and essential flow of time, associated with the above objective and subjective aspects of the world and with the ordered real continuum of equation 1, that we take as the starting point for the present theory. Analysis of the intrinsic arithmetic substructure of this continuum through the general form for infinitesimal intervals of proper time in equation 3 leads to a physical theory that can be explicitly and directly developed. That is, since the continuum of real numbers *has* this substructure of equation 3 time, as represented by $s \in \mathbb{R}$ in equation 1, also *has* this intrinsic substructure and the consequences may be explored.

Further, from an objective perspective everything we have been able to empirically determine about the world derives from data collected in an arena with three dimensions of space. This is the case from the smallest scale of experiments conducted in the laboratory to the largest scale of observations in cosmology. From the subjective point of view we might also consider that in order for the *perception* of a physical world to be even conceivable that perception must utilise a specific structure, which in our world takes the geometrical form of 3-dimensional space. This *need* for a locally Euclidean *spatial* arena implies a significant role for a *quadratic* form in the underlying mathematical construction of the universe to describe the appropriate geometric properties. This then addresses the question concerning *why* from the general form for proper time in equation 3 the substructure on the right-hand side of equation 2, projected out for the local structure of a background manifold via equation 4, should have the preferred mathematical properties of a quadratic form. This is seemingly *required* in order to *perceive* a world at all, and in turn implies theoretical constraints on the possible structures of the resulting physical universe.

The above subjective requirements are akin to the *a priori* notions of *time* and *space* that logically *precede* any experience we can have of a physical world as expounded in the philosophy of Immanuel Kant [33]. For Kant 'all appearances whatsoever, that is, all objects of the senses, are in time, and necessarily stand in time-relations.' ([33] A34/B51). A similar subjectivity is also argued for perception in space with Kant concluding that it is 'solely from the human standpoint that we can speak of space, of extended things, etc.' ([33] A26/B42). That all real events in the world are dependent upon the past as described by relations of *causality*, with causes temporally preceding effects, is for Kant a further *a priori* category of our understanding. (A deep-rooted sense of the significance of causality also provides one of the motivations for causal set theory as we noted shortly before figure 6).

For the present theory with all events subsumed within the flow of time the notion of causality is effectively subsumed into the concept of time, with the latter considered an ordered 'causal continuum' carrying a sense of 'before' and 'after'. It is the continuum property that allows the flow of time to be expressed directly in a spatial arena that *derives* from the properties of the real numbers and the intrinsic arithmetic substructure of time in the form of equation 2. Causality is then reflected in the resulting local spacetime structure of figure 4, incorporating a sense of 'past' and 'future', as well as in the extended spacetime as constructed for figure 7, with the implied local Lorentz symmetry properties as discussed for both cases.

The key requirement for the identification of a light cone structure, preserving causality as described for figure 4, is that there should be only one timelike coordinate x^0, that is with only one '+' sign in the local metric as for equation 2. However, such a quadratic form can be defined for any number d of spacelike coordinates with $(\delta s)^2 = \hat{\eta}_{ab}\delta x^a \delta x^b$ and the local $(d+1)\times(d+1)$ Lorentz metric $\hat{\eta} = \mathrm{diag}(+1, -1, \ldots, -1)$ of a $(d+1)$-dimensional spacetime. Hence while the '1' timelike component is uniquely determined a $(d+1)$-dimensional spacetime manifold M_{d+1} could consistently be constructed respecting causality for any $d = 1, 2, 3, \ldots$, with a corresponding Lorentzian symmetry, by direct analogy with the $d = 3$ case described for figures 4, 5 and 7. On these arguments the number of spatial dimensions d would appear to be arbitrary.

In the context of the present theory the symmetry breaking of equation 3 and the resulting properties of physical structures in the corresponding extended spacetime would however of course depend upon the choice of d. For the case of $d = 3$ and the branch of proper time leading to equation 6, in projecting out the local 4-dimensional spacetime form of equation 2 via the corresponding structure of equation 4, the resulting physical properties discussed for figure 8 underlie the stars, planets, chemistry and biology capable of sustaining an environment suitable for supporting observers such as ourselves. This particular case, with an external spacetime of *four* dimensions from a seeming range of possible choices, then frames a universe that *can* be observed and hence could be considered a mild form of anthropic selection.

As noted in section 1 an autostereogram exemplifies how a 3-dimensional spatial image can be perceived on viewing an appropriately constructed diagram in a 2-dimensional plane. Indeed figure 1 has been drawn in the manner of a simple autostereogram that can be viewed as a 3-dimensional perspective image apparently coming out from and floating above the page, on adjusting the convergence of the line of sight of a pair of eyes above the plane of the diagram, itself viewed from around twice the normal distance (see [34] for advice on how to view this figure as an autostereogram, for other examples, and for the references therein). The visual experience of a robust and stable 3-dimensional perception can be apprehended from figure 1 as the whole perspective image *fuses* into place, similarly as for viewing autostereograms more generally.

By analogy here the mathematical structure of the 4-dimensional quadratic form on the right-hand side of equation 2, as a substructure of the general form of time in equation 3 as realised through the branch of equation 6, provides our affinity to perceive the flow of time in a geometrical 3-dimensional spatial form with 'something to get hold of'. Here the fusing or locking of the full structure of matter in an extended 3-dimensional space is a much more profound and immersive experience since *our own physical form* is wholly embedded within the resulting material and spatial structure of the universe that we perceive. It is not something we can snap into and out of as for viewing an autostereogram.

The fact that we directly observe and 'live in' the branch of proper time of equation 6, rather than other possible branches such as those of equations 7 and 8, follows from the trivial anthropic selection effect that the physics of the Standard Model resulting from equation 6 can support life as we know it, leaving the gravitationally connected branches of equations 7 and 8 as an apparent dark sector. Within this visible sector of equation 6, the further mild anthropic choice of *four* external spacetime dimensions noted above may relate to the existence of stable planetary orbits for this case, as well as the appropriate chemistry and biology (see also [1] section 13.3).

It is possible that there may be a small number N_p of free parameters resulting from the symmetry breaking of equation 6 that determine details of the physical structure in the extended 4-dimensional spacetime. The 18 parameters of the Standard Model ([1] table 15.2), as well as those describing masses and mixing in the neutrino sector, would be expected to depend upon the set of N_p parameters in a well-defined way. Hence as long as $N_p < 18$, or ideally $N_p \ll 18$, this theory would still be predictive and testable within a further degree of anthropic selection. Indeed, such a situation with some leeway for anthropic selection might be preferable to a theory for which $N_p = 0$, implying the existence of a single unique universe which happens to have physical properties and parameters conducive to the existence of observers such as ourselves as a seemingly miraculous stroke of luck.

The key observation for the theory presented in this paper, as utilised in the above discussion, is that the form of space *out there* comes from *within* possible forms of time, very much contrary to any conception of time as something embedded within and flowing through a pre-existing geometric arena. A potential obstacle to envisaging how the whole universe can be created as a manifestation of the flow of time is perhaps the familiar depiction of time and a chronology of events as a one-dimensional line drawn in space. This long-standing representation of time is alluded to for example in the above cited 18^{th} century work by Kant, where it provides an analogy to compensate for the lack of any 'shape' associated with time itself ([33] A33/B50):

> We represent the time-sequence by a line progressing to infinity, in which the manifold constitutes a series of one dimension only; and we reason from the properties of this line to all the properties of time, with this one exception, that while the parts of the line are simultaneous the parts of time are always successive.

This remains a common and highly influential means of illustrating the apparent structure of time, that presents the risk of being taken as more than an analogy. However, while the space we inhabit can be literally conceived of as a 3-dimensional volume we *never* encounter time as a purely one-dimensional, more than 'razor-thin', line. Even in a local sense such a 'line of time' is a very crude and simplistic representation of how we actually perceive or measure the passing of time. A full understanding of the present theory involves a much richer conception of *what time is*, requiring a significant reassessment of the nature of time itself, as we elaborate in the following section. From the new perspective the flow of time can be seen to *accommodate* not only all 'shapes' but the form of space itself and the entire material structure through which we perceive the physical universe.

6 The Nature of Time: an Extensive Causal Continuum

Through history a clear definition of the concept of time has been notoriously hard to elucidate. This predicament is encapsulated in the well-known words of the philosopher St Augustine (354–430 A.D.) from book XI of his *Confessions*: 'What, then, is time? If no one asks of me, I know; if I wish to explain to him who asks, I know not.' ([35] book 2, chapter 4.I), expressing the familiar and yet enigmatic character of time. As noted at the end of the previous section in a theoretical context, as in everyday life, time is typically represented by a directed one-dimensional line in space, implicitly parametrised by a real number scale. This single temporal parameter serves as a passive background to events happening, whether historically in world affairs or in the context of scientific observations from laboratory experiments at the smallest scale to the largest scale of cosmological evolution, with no further mathematical structure for time of its *own* generally considered.

While we perceive events in a fully 3-dimensional space, when we think of a 2-dimensional or one-dimensional space we essentially conceive of a 2-dimensional plane or a one-dimensional line embedded in a 3-dimensional spatial volume. However, we never encounter an 'infinitely thin' 2-dimensional plane or one-dimensional line, or physical entities exactly confined to such spaces, with such notions considered an idealisation for certain situations that we do come across in our 3-dimensional spatial world. Similarly we never encounter an 'infinitely thin' line of progression in time, either as a line in 3-dimensional space or as a worldline in 4-dimensional spacetime associated with the propagation of an apparent point in space. A worldline in a diagram drawn with chalk or ink has a finite physical thickness (such as for the strands $s_{A,B,C}$ depicted in figures 7 and 8), it is not a vanishingly thin one-dimensional line. Hence we might ask to what a *purely* one-dimensional conception of time might correspond to in the world; where might it reside?

While the notion of a one-dimensional line might be conceivable this is not what time *is* in terms of anything we know of in the physical world or how we perceive the passage of time. For example there is no infinitely thin line of time through spacetime directly connected with a ticking clock; which infinitesimally small part of the clock would this involve? Even a single atom of the many composing an atomic clock is not a point-like entity. No device recording time is a purely one-dimensional timelike object in spacetime. Such an ideal worldline might be associated with the path of a classical point-like particle, however such an entity is an idealisation in itself, an abstraction from certain empirical phenomena, which is both theoretically problematic and not known to actually exist. Hence any one-dimensional time-line associated with any phenomenon only exists in our imagination as *abstracted* from the actual empirical situation, as a pragmatic representation or semantic device with no evidence of an explicit physical correlate.

Rather we are familiar with the passage of time, as for example objectively measured by clocks or subjectively experienced through activity of the brain, in all cases associated with a *distribution* of matter in an *extended* 3-dimensional spatial volume. That is, we *only ever* encounter time as flowing in a fully 4-dimensional spacetime form. The flow of time seemingly permeates the 4-dimensional spacetime arena rather like flowing water, considered as a continuum, fills the 3-dimensional volume of a river. In the present theory the flow of time *intrinsically* has this extensive property in a fully consistent manner with all matter and 4-dimensional spacetime itself *deriving* from *within* the causal continuum of time alone as described in the earlier sections and represented in figure 8.

From this perspective the simple and pragmatic representation of time drawn as a purely one-dimensional line in space, or as a worldline in spacetime, with nothing in the physical world precisely corresponding to it, is a poor approximation and may give a very misleading impression of the true nature of time. When we represent a one-dimensional space by a line in our 3-dimensional space this typically implies that we *are* referring to a substructure of 3-dimensional space that does not have more than one spatial dimension. By analogy when we represent time by a one-dimensional line drawn in space the implication may be falsely inferred that *time itself* necessarily lacks any higher-dimensional structure. If time was indeed a strictly vanishingly thin one-dimensional entity it would seem absurd that such a structure could subsume the full spatial extent of the universe and all of its material content. This familiar portrayal of time as an ideal one-dimensional progression with no spatial width of its own may then present something of a psychological barrier, impeding the adoption of a view conceiving of the full universe of physical structure throughout a potentially infinite 3-dimensional spatial extent as accommodated within and deriving *from* the flow of time alone. With time as the primary and fundamental entity this is the proposal of the theory presented here.

The essential property of time considered here is as a causal progression with all emphasis on the character of an ordered continuum. The continuum of time can be mapped onto the continuum of real numbers $s \in \mathbb{R}$ in equation 1, with the causal nature of time represented by the ordered structure of this real number parameter. This notion of time *could* be taken to mean that there is *no* associated spatial structure, but that is *not* a conclusion that is implied in this conception of time as an ordered continuum. That is, the idea of a causal continuum of time does not inherently preclude any spatial properties but rather does not say *anything definite* about such a spatial aspect, whether it is absent altogether or whether it may be arbitrarily extended in any number of spatial dimensions. This perspective on time should be approached without any *preconception* of its relation to spatial extension, and in particular not misled by any representation of time as a one-dimensional line embedded within a pre-established larger geometric framework.

Rather here with time as the sole fundamental entity of the theory any notion of spatial extension, or the lack of it, must be *deduced* from the properties of the causal continuum of time alone. While the ordered continuum of time can be described by the real parameter $s \in \mathbb{R}$ of equation 1 this *does not* imply any artificial *restriction* to a purely one-parameter structure *without access* to the arithmetic substructure innate in the real number system. The direct analysis of the continuum of equation 1 exhibits arithmetic substructures for infinitesimal intervals $\delta s \in \mathbb{R}$ including that of equation 2 *from* which the possibility of an extensive 3-dimensional spatial structure associated with the flow of time *can be inferred*. Hence the source generating the geometrical construction of space is implicit within the flow of time itself. As manifested in our universe the flow of time is then *not* something without spatial extent.

This spatial width is hence an inherent property arising from an elaboration of the flow of time as a causal continuum, as manifested in the full 3-dimensional spatial extent of our universe and in principle without limit in expanse, as is the case in modern cosmological models. As noted in the discussion of figures 4 and 7 such a spatial extension implies a temporal partial ordering of events in the resulting spacetime manifold, with an objective order strictly for events connected within the light cone structure while the apparent order of spacelike separated events is dependent upon the choice of reference frame. This structure, as described and constructed for figure 7, is then consistent with the overall causal propagation property of time as reflected in timelike worldlines, as exemplified by s_A, s_B and s_C, that can be identified passing through any location. While each is parametrised by a single real number such idealised worldlines do *not* represent the full nature of time, rather they are elements within the overall 4-dimensional spacetime manifold which itself derives from the internal structure of the flow of time.

As described towards the end of section 2, in section 3 and in the opening of section 4 the derivation of space from the flow of time via the local form of equation 2 implies a relativistic spacetime as 'one entity', rather than a Newtonian-like framework with independent space and time structures. Here that 'one entity' is fundamentally temporal. As described in section 4 this perspective implies the possibility of the further natural arithmetic generalisation for this temporal entity to the invariant form for infinitesimal proper time intervals of equation 3. Via these generalised elements of time in equation 3, and the explicit forms of equations 6, 7 and 8 that this can take, the construction of the extended 4-dimensional spacetime manifold M_4 as reviewed for equation 9 and figure 8 leads directly to the structure and composition of matter in spacetime deriving from the residual components over M_4. All matter from elementary particles to galactic formations, including physical clocks and observers, is hence encapsulated *within* the flow of time as expressed through equation 3 and realised in this extended spacetime form.

On adopting this approach to a physical theory highly non-trivial connections with empirical observations in our universe have been established, as reviewed in section 4. This physical universe is also profusely filled with timelike worldlines, such as s_C in figure 8, through being constructed purely from the flow of time. Again, while we begin with the progression of time as the continuum $s \in \mathbb{R}$ in equation 1 *this* is *not* a parameter embedded in anything or attached to any physical object as a single worldline in spacetime. That is, here time is very much *not* conceived of as threaded through a pre-existing spacetime to parametrise the evolution of pre-existing forms of matter. Rather, with the whole universe deriving from this fundamental flow of time any line drawn in space or through spacetime gives a very limited and inadequate representation of the full structure of time.

The tendency to consider time as being somewhat like space, in being represented by a line drawn in space, is sometimes called the 'spatialisation of time'. It suggests that time can be thought of as 'another dimension' as a geometric augmentation to the three spatial dimensions, as employed in particular for describing the location of events in the 4-dimensional spacetime of relativity. This also suggests that time can be incorporated into a complete and 'fixed' geometrical structure, rather than considered as a 'flowing' entity, as we shall discuss further in the opening of the following section. This geometric picture applies in particular for *coordinate* time x^0, such as described for figures 3 and 4.

Here, in placing the focus on *proper* time s, rather than time being 'like' space we have the *opposite* proposal, with the continuum of 3-dimensional space itself deriving from the causal continuum of time via the local structure of equation 2. Through this 'temporalisation of space' the entire 4-dimensional spacetime manifold can be constructed as a manifestation of time as described for figure 7, crucially retaining the causal continuum properties as inherited from the underlying ordered temporal flow. It is this change in perspective that allows the direct generalisation from equation 2 to equation 3 which provides the source for not only space but also a matter content as also participating in the causal progression as described for figure 8.

By way of demonstrating these distinctive ways of looking at time we consider the following fanciful yet illustrative context. The notion of time as a line drawn in space to represent historical events is sometimes used as a device in the science fiction genre of adventure stories to make the idea of 'time travel' sound more plausible – arguing that a machine might be constructed capable of 'tuning in' to any point of the past or future as laid out along such a 'time-line'. Such an idea is even *less* plausible here for the notion of time as a causal continuum, with all physical entities and all 'machines' caught up *within* the flow of time and with no means of *stepping outside* this structure, as would be the case for a mere line in space. (In a related manner the possibility of a 'time machine' is explicitly ruled out in causal set theory essentially by the mathematical definitions of that framework [36] section III.C).

More prosaically, drawing time geometrically as a directed line in space may also contribute to the impression that time *could* flow in the 'opposite direction', similarly as a spatial line can be directed in either of two opposing ways. That is an arrow drawn on a time-line to indicate succession could seemingly be equally placed with the opposite sense. This suggestion is reinforced by the elementary equations of physics, such as for Newton's laws, relativity and the Schrödinger equation, which are symmetrical under time reversal with identical properties in the evolution of a state back to earlier times as for forward to later times ([7] section 27.1). This is in stark contrast with the macroscopic empirical world in which there is a clear asymmetry between the past and the future. This corresponding 'arrow of time' is generally associated with the second law of thermodynamics and very special low entropy initial state conditions for the universe in the Big Bang ([7] section 27.13).

For the present theory time does *not have* an 'arrow' or a 'direction', those are purely terms that apply in a spatial context. Rather time, as a causal continuum, is simply a *progression*, with *no conceivable* 'other direction'. In beginning with a state of low entropy the overwhelming statistical likelihood is for that value to increase with the temporal progression, while an isolated maximum entropy system can only evolve into states with the same entropy within statistical fluctuations. The fact that at an elementary level the dynamical equations of physics are symmetrical under time reversal is a feature of the simplicity at the level at which those equations apply, contributing to the illusion that time itself could in some sense have a reverse direction. Ultimately all equations of motion and laws of physics describing the properties of matter in spacetime derive from the ordered progression of the flow of time as an all-embracing causal continuum (see also discussion just after figure 8).

Hence here *time* is not something that can be isolated and unambiguously identified as an entity *in* the world or pointed to within the context of *things* in the physical world generally. Attempts to do so lead to a confused or incoherent picture, as alluded to with reference to the historical quote from St Augustine in the opening of this section. Rather the enigmatic quality of time essentially stems from the fact that time is *everything*, encompassing all, with the entire physical world literally a representation *of* and *within* the flow of time. With the universe conceived of as a manifestation of the extensive causal continuum of the flow of time itself, subsuming not only spacetime but also the entire matter content, this then provides a highly unifying framework for a physical theory, as we elaborate in the following section.

7 Unification as a Theory of Time

Two complementary conceptions for ways of looking at the universe are sometimes presented. One of these involves the description of a *block* universe as a 'fixed' 4-dimensional spacetime object encompassing the full past and future development as well as the full spatial expanse of the cosmos. The other is in terms of an active *dynamical* evolution of all physical entities in 3-dimensional space, and even the geometry of spacetime itself, as parametrised by a temporal progression, providing a model closer to the manner in which we directly perceive the universe. A prime example of the former worldview is seen in full 4-dimensional spacetime solutions for the Einstein field equation of general relativity, while the latter viewpoint is exemplified by the evolution of a state in time according to the Schrödinger equation in quantum theory – with these contrasting perspectives marking one of the significant difficulties in establishing a coherent theory of quantum gravity as associated with the 'problem of time' (see discussion in [29] subsection 2.3 and references therein).

In a philosophical setting the block universe picture is sometimes likened to 'being' while the dynamical evolution picture is associated with 'becoming' (and the ancient proponents Parmenides and Heraclitus respectively, see for example [35] book 1, chapters 5 and 4, [37] Introduction). 'Being' then corresponds to a 'timeless' or 'frozen time' block universe as connected with the apparent implications of relativity and in which the 'flow of time' is considered an *illusion*. 'Becoming' describes a world in which evolution, change in time and the dynamical perspective are fundamental, with time *really* passing or flowing.

A desire to amalgamate these two worldviews in a coherent manner, as well as to provide a framework for quantum gravity as noted in section 3, provides some of the motivation for causal set theory [21, 38, 39]. In that approach the entire 'past' can be considered a block universe that is dynamically *growing* by a 'percolation' or 'cosmological accretion' of new atoms of spacetime coming into being as 'offspring' of existing causal set elements in the past. At the local level, at the forefront of such an accretion, this would involve new spacetime atoms and causal links appended on the right-hand side of figure 6(b). This physical and objective growth of the block does not *happen* in time, rather it *constitutes* time. That is, the phenomenological passage of time *is* a manifestation of the continuing growth of the causal set. The occurrence of a physical event, such as a supernova exploding, is identified with the partially ordered birth of the corresponding atoms of spacetime, with any necessary accompanying matter degrees of freedom born with them [38].

In the present theory the above 'block' and 'dynamical' worldviews are effectively combined in a rather different and contrasting manner, while also describing an overall coherent framework. From the properties of time as a causal continuum as the fundamental entity the full 'past and future' matter distribution in a 4-dimensional spacetime 'block' M_4 is built entirely out of infinitesimal elements of the flow of time, via equation 2 subsumed into equation 3 as described for figures 4, 5, 7 and 8 and generating the extended geometry of equation 9, with each location of M_4 hence embodying an intrinsically 'dynamical' temporal structure. We again note the analogy alluded to in the previous section of the 'fixed' geological structure, including the bed and banks, of a river that contains an everywhere 'flowing' body of water.

Here it is the flow of time itself that provides the source for both the geometry of spacetime and the structure of matter. Wherever an observer is located in the full M_4 block a flow of time will be experienced as a 'sliding now', such as exemplified by anybody in the process of reading these words. Similarly a physical clock inserted anywhere in the 4-dimensional block will 'tick'. There is hence no difficulty in conceiving of how the 4-dimensional spacetime block universe can be consistent with a dynamical flow of time since the former contains everywhere throughout a locally inexorable and continuous progression in time *from which* it is constructed.

This framework is then also consistent with the manner in which we encounter the universe through the experience of a local flow of time. (For speculation on the role our experience of time passing might itself play see [1] chapter 14, where for example [1] figure 14.7 can be compared with figures 7 and 8 here). While our subjective sense of a 'sliding now' is perhaps of order one second in duration, beyond this experience we can conceive of time intervals $\delta s \in \mathbb{R}$ taken to the infinitesimal continuum limit and mathematically analysed as described for equation 3, with the world constructed from such infinitesimal moments of time as the basis for the development of a full physical theory that can be rigorously tested against experiments. On the other hand from our observations of the world and deductions regarding the large scale structure of the cosmos we can also readily conceive of the past 13.8 billion years of cosmic time history of the universe together with its projected future development within a full 4-dimensional block picture. This perspective was effectively discussed for figure 8 towards the end of section 4, with the universe spanning from the Big Bang to a potential Big Rip (see also for example [1] figure 14.8 and discussion).

While the 'block' and 'dynamical' conceptions of the universe, and our place within it, are hence reconciled and synthesised in this theory, as a unification scheme there are broader implications for fundamental physics. These include an approach to quantum gravity in the context of which rather than a 'problem of time' here we essentially have a 'theory of time' ([29] subsection 7.1). This framework coherently combines global geometric 4-dimensional spacetime solutions, as associated with general relativity, with a temporally ordered progression in probabilistic outcomes for structures of matter at the local level, as associated with quantum phenomena, resolving the compatibility issue described in the opening of this section. More generally for any proposed candidate theory combining gravity with quantum theory a key aspect concerns the interrelations implied between space, time and matter (see for example [40]).

In table 1 below and in the following discussion we have summarised the historical progression in conceptions of space, time and matter, and the relations between them, as ever converging towards a more unified worldview.

	Conceptual Relations	Theoretical Context	Role of Time s
1)	space time matter	Newtonian physics	$s \in \mathbb{R}$ absolute
2)	spacetime matter	special relativity	$(\Delta s)^2 = \eta_{ab}\Delta x^a \Delta x^b$ globally
3)	spacetime matter	general relativity	$(\delta s)^2 = \eta_{ab}\delta x^a \delta x^b$ locally
4)	spacetime matter	extra space dimensions	$(\delta s)^2 = \hat{\eta}_{ab}\,\delta x^a \delta x^b \quad n > 4$
5)	space time matter	generalised proper time	$(\delta s)^p = \alpha_{abc\ldots}\delta x^a \delta x^b \delta x^c \ldots \quad p > 2$

Table 1: Relations between space, time and matter through a series of historical developments. 1) Independent and absolute 3-dimensional space and one-dimensional time with a matter content in classical mechanics. 2) Space and time combined into a global flat 4-dimensional Minkowski spacetime. 3) The global curved geometry for spacetime in dynamic interplay with matter through the Einstein field equation $G^{\mu\nu} = -\kappa T^{\mu\nu}$. 4) Kaluza-Klein theories in n-dimensional spacetime subsuming 4-dimensional spacetime and a matter content. 5) The proposal of generalised proper time, dropping the assumption of a quadratic form, as the progenitor of both space and matter.

The progression from an arena of absolute space and time, the latter representable by equation 1 here, as had been established in Newtonian physics since the late 17$^{\text{th}}$ century [41], to the 4-dimensional spacetime of special relativity, as developed in the early 20$^{\text{th}}$ century, introduced the definition of proper time intervals $\Delta s \in \mathbb{R}$ of arbitrary length inextricably connecting space and time through global Lorentz transformations [42]. Through the equivalence principle and local flatness of general relativity the Lorentzian metric form of this relation strictly holds only in the limit of local infinitesimal intervals $\delta s \in \mathbb{R}$, as can be expressed by equation 2 here, with the curved geometry of the extended spacetime dynamically linked with the distribution of matter through the interplay described by the Einstein field equation [43].

Motivated by the pursuit of a unification of gravity with the other forces of nature, and extending upon the original idea of Kaluza and Klein from the 1920s [2, 3], since the 1970s many models with extra space dimensions have been proposed to accommodate structures of matter (see for example [4, 5, 6]). With the local Lorentzian quadratic form for δs augmented to an $(n > 4)$-dimensional local spacetime structure, with a local $n \times n$ Lorentz metric $\hat{\eta} = \text{diag}(+1, -1, \ldots, -1)$, the properties of matter fields derive from the structure of the extra dimensions of space over and above 4-dimensional spacetime, as reviewed for figure 1. However, no decisive empirical success or support for such a framework has been found (see discussion in [25] subsection 2.1 and references therein).

For the present theory we further generalise the local expression for proper time intervals δs to equation 3, as is freely arithmetically permitted, dropping the *assumption* of a quadratic form since this is not required for the components that are not perceived as spatial dimensions ([25] subsection 2.2). This generalised form for proper time with homogeneous polynomial power $p > 2$ can then directly accommodate both 4-dimensional spacetime and a matter content through the symmetry breaking described for equations 4 and 5, without the need to posit *any* further structure, culminating in the picture of figure 8 (see also for example [25] subsection 2.3). This approach can itself also be seen as a direct and natural generalisation from general relativity ([25] subsection 5.1 and in particular figure 2).

On dropping the global flat spacetime assumption of special relativity a significantly more complex mathematical structure, involving differential geometry, was required to describe the extended curved spacetime geometry which, however, in the form of general relativity, could account directly for the force of gravity, without any further structure needed. In the present theory we utilise a complementary generalisation, on dropping the assumption of the local quadratic form employed for extra spatial dimensions and deploying the general form for proper time in equation 3. This again initially leads to a more complicated mathematical structure, involving exceptional Lie group symmetries through to the proposal of equation 6, but has the significant merit of leading directly to structures of the Standard Model, again without the need to introduce any further construction. As reviewed in section 4, this approach has scored a series of empirical successes, with an ability to directly account for features of not only the Standard Model but also the dark sector, as well as provide a candidate quantum gravity framework.

Quantum theory, originally formulated in a background of non-relativistic space and time, could be made compatible with special relativity with the significant predictive successes of quantum field theory, albeit with the need for an extended mathematical toolkit to deal with issues such as infinities arising in the calculations. However, a similar degree of success has not been achieved for a consistent amalgamation of quantum theory with general relativity. Rather, the search for a coherent and definitive quantum gravity theory has proven to be technically much harder and to date remains inconclusive. The present theory then provides a new opportunity to construct a quantum gravity framework, as reviewed in section 4 and noted above. Here with quantum phenomena described in a curved spacetime, as consistent with general relativity through equation 9, the aim is to reconstruct the structure of quantum field theory in a flat spacetime approximation. In the process the aim is also to address technical mathematical issues, for example concerning the infinities alluded to above, as well as the long-standing conceptual and interpretational questions relating to quantum theory generally [29].

Models with extra spatial dimensions typically begin with an n-dimensional bulk manifold within which an external and extended 4-dimensional spacetime manifold is embedded whole, as reviewed for figure 1. Here by contrast, with the local infinitesimal spacetime form of equation 2 and figure 4 embedded in the general form for infinitesimal proper time intervals of equation 3 via equation 4, the extended 4-dimensional spacetime is built up from the local level. While this emphasis upon local structure could be considered a common feature with causal set theory, as discussed in relation to figure 6, here this construction is continuous and leads to a smooth 4-dimensional spacetime manifold on all scales, with causality and all causal relations between events also subsumed under time as an extensive causal continuum, as described for figures 5 and 7. This local and continuous construction, and the composition of the resulting spacetime arena M_4, is key to the empirical and theoretical successes of the new approach with the flow of time as the underlying fundamental basis.

Given that there remains no evidence for the existence of extra dimensions of space the spatial nature of the extended geometrical construction employed in such a model may be unnecessarily restrictive. Such models typically also suffer from a great deal of arbitrariness in the means of *compactifying down* to, or otherwise extracting, the external 4-dimensional spacetime base, with a potential vast 'landscape' of possible solutions and very limited predictive power. Here by contrast in *building up* the extended 4-dimensional spacetime from local elements of proper time there is again a great deal of arbitrariness in this geometric construction and the associated matter composition, as consistent with general relativity, through equation 9. However, this redundancy and degeneracy in solutions presents a significant benefit in this theory in underlying the uncertainty and indeterminacy of empirical quantum phenomena.

While the approach of extra spatial dimensions may sound more plausible, in that there are many ways to construct such extended structures and then extract a 4-dimensional spacetime base with an apparent matter content, no compelling empirical connections have been obtained this way as noted above. On the other hand, the potential seeming implausibility of constructing a theory based on time alone, through generalised proper time, implies that any possible means of construction will be more unique and constraining. These are very much features desired in a unified theory and it is precisely within these constraints that the empirical successes, including the direct connections with the Standard Model and the dark sector, are obtained.

The historical developments in table 1 begin at stage '1)' with the three independent basic entities of space, time and matter, as indicated by the three independent enclosing ovoids drawn in the first column. As a progression towards a more unified worldview in the relativistic stages '2)' and '3)' these are essentially reduced to just two basic entities, namely 4-dimensional spacetime and matter, with a close link between these in stage '3)'. At stage '4)' in table 1 there is a further reduction down to a single basic entity, as indicated by the larger encompassing ovoid, in the form of a higher-dimensional spacetime framework. Specifically it is the 3-dimensional *spatial part* of a proper time interval that is generalised and extended to accommodate a matter content through structures of additional dimensions of space. However, the construction of an extended higher-dimensional spacetime does *not* represent a simple fundamental entity as would be desirable as a basis for unification.

For the final step to stage '5)' the *whole* 4-dimensional local expression for *proper time* is augmented, as can be interpreted as a generalisation from models with extra spatial dimensions and as a natural further progression on the trajectory towards unification. In this manner it is proposed that not only the matter content of our world but also the external 3-dimensional space in which it is distributed as well as all causal relations can be subsumed under *time* as the single basic entity. Time *does* represent both a very simple and familiar entity, as described in the opening of section 5, and is hence highly suitable as the basis for unification. Compared with extra spatial dimensions, the proposal of generalised proper time then presents a more unifying, simple, unique and conservative approach to unification that also *works* far better in terms of direct empirical successes.

Rather than beginning with a *multiplicity* of space dimensions as for Kaluza-Klein models, the present approach as a theory of time can be interpreted as being based on '*one* dimension' only [1]. While the *linear* flow of *time* of equation 1 and stage '1)' in table 1, with intervals $\delta s \in \mathbb{R}$, still represents the usual everyday way in which we think of and employ time, the *quadratic* form for $(\delta s)^2$ of equation 2, introduced for stages '2)' and '3)', brings *time* into direct relation with the geometric form of *space*. However, the motivation for extensions beyond this 4-dimensional spacetime form is *not* to incorporate more space but rather a structure of matter, for which there is no reason to impose a quadratic form. Hence a further natural progression is possible beyond the restricted spatial extensions of stage '4)' to stage '5)', allowing for $p > 2$ in expressions for $(\delta s)^p$ in equation 3, with the original three dimensions of *space* still identified via a quadratic substructure while incorporating a basis for physical structure of *matter* within this unified framework based on generalised proper *time* (see also [30]). With the notion of time, more specifically as a causal continuum alone, being the *simplest* of the three original basic entities of space, time and matter, and with the scope of unification extended to include space itself as well as matter, this clearly offers a more *unifying* scheme as consistent with the ideal notion of a unified theory ([32] section 1, criteria 1 and 2).

Since we begin simply with a continuous progression in time as directly represented by the real numbers with $s \in \mathbb{R}$ in equation 1 this provides a direct connection between the basic conception of the theory and a mathematical realm. Via the spacetime form of equation 2 through which a physical world *can* be perceived and unique mathematical instantiations for equation 3 the development of the theory leads to direct connections with the empirical world without needing to artificially postulate further mathematical structure. As noted in section 4 the theory directly accounts for an application of the exceptional Lie groups and the octonions for example in playing a central role in particle physics. As reviewed there the local symmetry breaking, as explicitly analysed through to a $\hat{G} = \mathrm{E}_7$ symmetry level, results directly in elementary properties of the resulting matter fields that closely resemble structures of the Standard Model [23, 24]. These developments generate a mathematical prediction for a realisation of $\hat{G} = \mathrm{E}_8$ as the ultimate symmetry for this branch of generalised proper time culminating in equation 6, leading in turn towards empirical predictions for new physics in this visible sector [25, 26]. The other possible branches of generalised proper time in equations 7 and 8 directly lead to candidates for dark matter and dark energy, interacting with the visible sector of equation 6 via the common 4-dimensional spacetime root [27]. Such a direct and unique mathematical development is also consistent with the objectives of a unified theory ([32] section 1, criterion 3).

This unification scheme based on generalised proper time also leads to the identification of a matter composition that is directly related to the extended spacetime geometry as described for equation 9, for a globally curved and locally flat 4-dimensional spacetime manifold M_4 as consistent with the equivalence principle, hence incorporating a direct connection with general relativity. The construction of this continuous spacetime from the local level is central to the identification of quantum properties for all non-gravitational fields as deriving directly from the nature of the matter composition, in place of introducing a postulated 'quantisation' formalism, hence establishing a proposed quantum gravity framework [29]. All of these empirical features are also of course desired of a unified theory ([32] section 1, criteria 4 and 5).

8 Summary and Conclusions

In a series of previous papers (including [8, 23, 24, 26, 27, 29], [25] sections 3 and 4) we have developed the connections of the present theory with established theories and with the empirical world, while in others (such as [30, 32], [25] section 5) we have described the shift in conceptual relations between space, time and matter underlying this approach and as appropriate for a unified theory. The aim of this paper has been to present the broad perspective of how the universe is realised and functions for this approach based on generalised proper time, with the emphasis more directly on the elementary construction of the world and the conception of the *nature of time itself* as an extensive causal continuum in this theory.

Here the fundamental nature of time is simply an ordered progression that can be described by the real continuum of equation 1. The properties of this continuum include the arithmetic possibility of expressing infinitesimal intervals $\delta s \in \mathbb{R}$ in the form of equation 2 as an intrinsic substructure of time. From this perspective the flow of time itself can generate a spatial form and it is not necessary to artificially append *any* dimensions of space, as initially discussed for figure 3 in section 2. The arithmetic form of equation 2 with four components $\{\delta x^a\} \in \mathbb{R}^4$ can be *interpreted* as describing a geometric light cone representation of the causal structure of time in a local 4-dimensional spacetime as described for figure 4 in section 3.

While the intervals $\delta s \in \mathbb{R}$ fit together along the real line, such as pictured in figure 3, the elements of time with $(\delta s)^2 = \eta_{ab}\delta x^a \delta x^b$ in equation 2 are mutually related and engage together in $\mathbb{R}^4$, either generating the global Minkowski spacetime of figure 3 or through the more general assembly from the local level as described for figure 5. The contiguous 4-dimensional extension of this latter construction generates the extended and generally curved spacetime manifold M_4 of figure 7 which, via the local metric structure of equation 2, is imbued with locally Euclidean 3-dimensional spatial properties through the three components $\{\delta x^1, \delta x^2, \delta x^3\}$, with the resulting manifold also respecting the causality properties of time. There is hence nothing in the nature of time as a causal continuum that precludes the flow of time being manifested in the form of an extended 4-dimensional spacetime arena in this manner as described in detail in section 3.

As a stepping stone en route in describing this construction a transitory analogy with causal set theory, for which a notion of temporal causality also takes priority, was discussed via figure 6. This comparison with the well-established approach of causal set theory is intended to clarify what is involved in building an extended spacetime from more basic elements. While the causal set approach employs structureless events or ‘atoms of spacetime’ that are then linked by causal relations, as briefly reviewed for figure 6, here the basic elements are the infinitesimal ‘atoms of time’ of equation 2 that carry their *own* causal structure. Further, in contrast with the resulting discrete spacetime of causal set theory, here the construction is taken to the continuum limit with the elements of time of equation 2 and figure 4 meshing together to generate a continuous and everywhere smooth spacetime as described for figures 5 and 7. This leaves no residual physically distinct ‘atoms of time’ with a discrete individual identity, rather such entities as employed in this description dissolve away and are assimilated into the fabric of the continuous extended 4-dimensional spacetime constructed.

The nature of the continuum structure of time down to the infinitesimal intervals of equation 1 also implies the direct arithmetic generalisation from the form of time in equation 2 to that of equation 3 as the general form of proper time. The residual components of this general form, over and above those describing the local 4-dimensional spacetime substructure, provide the basis for matter fields in the extended spacetime as reviewed in section 4. One advantage of this approach is that it leads so directly and inevitably to such a source of matter (see also [32] figure 1). The identification and structure of this matter then depend upon the symmetry breaking structure deriving from the necessary projection of the now intermediate form for proper time on the right-hand side of equation 2 out of equation 3 to construct the external spacetime manifold, as described for equations 4 and 5.

The actual analysis of the full symmetry breaking for explicit mathematical forms for equation 3 over the local form for 4-dimensional spacetime, and deduction of the resulting matter field properties, has been carried out in practice after first rewriting this general expression for infinitesimal proper time intervals in the equivalent form (see for example [23] equation 43, [29] equation 28, as we note here for connection with the earlier references):

$$L_p(\boldsymbol{v}_n)_{\hat{G}} \;:=\; \alpha_{abc\ldots}\frac{\delta x^a}{\delta s}\frac{\delta x^b}{\delta s}\frac{\delta x^c}{\delta s}\ldots\Big|_{\delta s\to 0} \;=\; \alpha_{abc\ldots}v^a v^b v^c\ldots \;=\; 1 \tag{10}$$

In this notation p is the homogeneous polynomial power, n is the total number of components and $\hat{G}$ is the full symmetry group for this general form for proper time. This symmetry acts upon the vector $\boldsymbol{v}_n \in \mathbb{R}^n$ of n components $v^a := \frac{\delta x^a}{\delta s}\big|_{\delta s\to 0}$, which being generally finite and associated with matter fields in spacetime provide a convenient means of investigating the local symmetry breaking structure and physical consequences.

The matter content has been determined explicitly for natural mathematical augmentations from the Lorentzian form of equation 2 to equations 3 and 10 for an explicit branch employing a full $\hat{G} = \mathrm{E}_6$ and on to a $\hat{G} = \mathrm{E}_7$ symmetry, leading to the proposal of an ultimate $\hat{G} = \mathrm{E}_8$ in equation 6. As also noted in section 4 the theory is then found to have broad explanatory power in accounting for non-trivial elements of the Standard Model of particle physics [23, 24] while also pointing to new physics beyond [25, 26]. These successes, hinging on the structure of equation 10, in turn substantiate the conception of time as a *continuum* down to arbitrarily small scales as employed here. As further evidence for the effectiveness of this theory, given the general nature of equation 3 there are further possible branches for proper time as described for equations 7 and 8, involving hidden compact and non-compact gauge groups respectively, that may account for the dark sector in cosmology [27].

As reviewed for equation 9 the construction of an extended 4-dimensional spacetime continuum results in a framework capable of convolving the geometric structure of general relativity with the probabilistic quantum phenomena of matter, as deduced in a suitable laboratory limit and for the general case, providing a candidate theory for quantum gravity [29]. While the extended spacetime is itself continuous on all scales, the constraints implied in this construction can also generate the discrete elements of the properties of matter that are characteristic of quantum phenomena. Hence, with the above physical structures collectively described for and represented in figure 8, a unified physical theory based on generalised proper time has been established.

All of this physics is conditional on the necessary projection from equation 3 of the local 4-dimensional spacetime substructure of equation 2 via equation 4 and corresponding symmetry breaking of equation 5, as required in order to perceive a world at all in *time and space* as we have discussed in section 5. In deriving *from* the flow of time alone, matter and spacetime are both here conceived of as manufactured from *within* the temporal progression. This is very much contrary to any notion of time as merely parametrising material evolution as a purely 'one-dimensional line' passing through space or spacetime while lacking any spatial width of its own, as might be represented by any of the worldline strands s_A, s_B or s_C depicted in figures 7 and 8. While there is no explicit empirical support for such idealised 'lines of time' the familiarity of such a representation could nevertheless be very misleading in terms of understanding the full nature of time as expounded in the present theory.

To further elucidate the structure of this theory in section 6 we have hence elaborated on the pertinent conception of time itself as an extensive causal continuum and the corresponding implications. Here far from any preconceived notion of time as merely a real number label parametrising the evolution of matter in space, time is the basic entity within which extended spacetime and the entire material world is itself enfolded and out of which it is fabricated. On adopting such a worldview with time as an all-embracing entity as proposed here a highly unifying physical picture can be established, as described in section 7. As discussed there for table 1, this approach of stage '5)' can be argued to be a natural culmination of the historical progression towards a fundamental unification scheme. We conclude with a summary of three main arguments supporting the case for this approach to unification:

Simplicity: A factor in this proposal is the simplicity and uniqueness of time as the basic entity underlying the universe, contrasting with the many conceivable forms of matter or structures of extra space dimensions. Given that this basis might seem *too simple* for a comprehensive unified theory, in this paper we have aimed to clarify the construction involved through an explicit exposition from an elementary level as described from equation 1 and through sections 3 and 4.

Empirical: Analysis of the physical content of the theory establishes non-trivial connections with the Standard Model and a dark sector far more directly than is typically the case for models with extra spatial dimensions, causal set theory or in other approaches. The resulting unified theory also provides a proposed scheme for quantum gravity and incorporates all scales from elementary particle interactions to cosmological structure, as summarised in section 4.

Historical: The progression in conceptual relations between space, time and matter in converging towards a more unified worldview, as discussed for table 1 in section 7, also points towards this proposal of building a physical theory based upon time alone as the fundamental unifying entity. Long-standing philosophical reflections on the nature of time provide a further backdrop to the understanding of the role of time developed here, as noted in sections 5, 6 and 7.

The sheer simplicity of time as the basic entity underlying the construction of the world could make the idea seem highly implausible and act as a significant barrier to the adoption of this approach. Indeed this proposal involves conceiving of the entire universe *as* a fundamentally temporal entity deriving from equation 1. This paper has been motivated largely as an attempt to describe how this is indeed possible by explicitly developing the construction of the theory from the most elementary level. In short, we have first shown how an extended 4-dimensional spacetime structure can be built up from the elements of time in equation 2 via the discussion of figures 3, 4 and 5 leading to figure 7, and then a matter content has been derived and filled in through the generalised elements of proper time in equation 3, taking the expicit forms of equations 6, 7 and 8, and through the composition of equation 9 as described culminating in figure 8.

We have attempted to clarify the basic structure of the theory by emphasising how this unification through a 'theory of time' elucidates the nature of time itself. We have shown explicitly how it is *possible* to construct a theory from the causal continuum of temporal progression alone, and briefly reviewed the highly encouraging features of the specific empirical connections attained. From this perspective the whole universe can be seen to be encapsulated *within* and to derive *from* the flow of time alone as the fundamental basis underlying a comprehensive unified physical theory.

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