ON THE PHYSICAL BASIS OF COSMIC TIME

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Abstract

In this manuscript we initiate a systematic examination of the physical basis
for the time concept in cosmology. We discuss and defend the idea that the
physical basis of the time concept is necessarily related to physical processes
which could conceivably take place among the material constituents available
in the universe. As a consequence we motivate the idea that one cannot, in a
well-defined manner, speak about time 'before' such physical processes were
possible, and in particular, the idea that one cannot speak about a time *scale*
'before' scale-setting physical processes were possible. It is common practice to
link the concept of cosmic time with a space-time metric set up to describe the
universe at large scales, and then define a cosmic time t as what is measured
by a comoving standard clock. We want to examine, however, the physical
basis for setting up a comoving reference frame and, in particular, what could
be meant by a standard clock. For this purpose we introduce the concept of
a 'core' of a clock (which, for a standard clock in cosmology, is a scale-setting
physical process) and we ask if such a core can—in principle—be found in the
available physics contemplated in the various 'stages' of the early universe.
We find that a first problem arises above the quark-gluon phase transition
(which roughly occurs when the cosmological model is extrapolated back to
$\sim 10^{-5}$ seconds) where there might be no bound systems left, and the concept
of a physical length scale to a certain extent disappears. A more serious
problem appears above the electroweak phase transition believed to occur at
$\sim 10^{-11}$ seconds. At this point the property of mass (almost) disappears and
it becomes difficult to identify a physical basis for concepts like length scale,
energy scale and temperature – which are all intimately linked to the concept
of time in modern cosmology. This situation suggests that the concept of a
time scale in 'very early' universe cosmology lacks a physical basis or, at least,
that the time scale will have to be based on speculative new physics.

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1 Introduction

Most cosmologists would agree that the physics describing the 'material content' of the universe becomes increasingly speculative the further we go back in time. By contrast, it is widely assumed that the concept of time (and space) itself – by virtue of a cosmological space-time metric – can be safely extrapolated sixty orders of magnitude back from the present to the Planck scales. Apart from some interesting hints in Misner, Thorne, and Wheeler (1973) (see also Misner 1969), we have found no discussions in cosmology which address the issue of whether time, like the physical description of the material content, could become more and more speculative as we go back in 'time'. Studies addressing the time concept at the Planck scale are of course abundant, cf. the problem of time in quantum gravity and quantum cosmology. But what we want to question here is whether the time concept is well-defined as a physical concept in cosmology 'before' (in the backward extrapolation from the present) the Planck scale is reached. The guiding question is thus: How far back in time can we go while maintaining a well-defined time concept?

It is standard to assume that a number of important events took place in the first tiny fractions of a second 'after' the big bang. For instance, the universe is thought to have been in a quark-gluon phase between $10^{-11} - 10^{-5}$ seconds, whereas the fundamental material constituents are massless (due to the electroweak (Higgs) transition) at times earlier than $\sim 10^{-11}$ seconds. A phase of inflation is envisaged (in some models) to have taken place around 10^{-34} seconds after the big bang. A rough summary of the phases of the early universe is given in the figure:
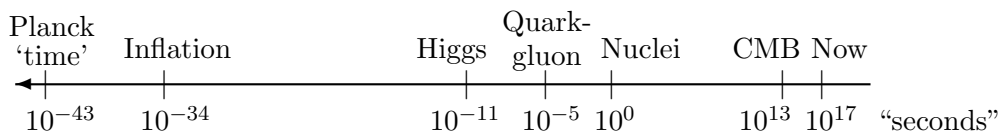
While the various phases indicated in this figure will be discussed in some detail in the present manuscript, a few comments and clarifications should be made here:

(i) The figure is to scale, that is, it captures e.g. that it is (logarithmically) *shorter* from the present back to the Higgs transition – which more or less indicates the current limit of known physics (as explored in Earth-based experiments) – than from the Higgs transition back to the Planck time located at $(\hbar G/c^5)^{1/2} \sim 10^{-43}$ seconds. This illustrates just how far extrapolations extend in modern cosmology![1]

(ii) Whereas one usually speaks of time elapsed *since* the big bang, the observational point of departure is the present – hence the direction of the arrow (we extrapolate backwards from now). For lack of viable alternatives, however, we shall

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[1]Prior to $\sim 10^{-2}$ seconds 'after' the big bang (the beginning of primordial nucleosynthesis) there is no clear-cut *observational* handle on physics in the cosmological context, see e.g. Kolb and Turner (1990, p. 74). The gap between this point and the Planck time spans 41 orders of magnitude. (After the COBE and WMAP experiments, however, it is widely believed that inflationary models may have observational signatures in the cosmic microwave background radiation (CMB)).

in the following use the standard time indications from the big bang (we shall thus also speak about 'seconds after the BB').

(iii) The quotation marks around seconds are included since, as we shall discuss, it is far from straightforward that one can 'carry back' this physical scale as far as one would like.

An objection to the study we propose might be that if time is well-defined within the Friedmann-Lemaître-Robertson-Walker (FLRW) metric, standardly taken to describe the present universe (at large scales), there seems to be no problem in extrapolating this time concept back to $t = 0$ or, at least, to the Planck time. However, this objection disregards that the FLRW metric is a mathematical model containing a parameter t which is *interpreted* as time. Whereas, as a mathematical study, one may consider arbitrary small values of t, our aim here is precisely to investigate under what conditions – and in which t-parameter range – one is justified in making the interpretation

$$t \quad \leftrightarrow \quad \text{time}.$$

In this paper we shall motivate and discuss the suggestion that a physical condition for making the $t \leftrightarrow$ time interpretation in cosmology is the (at least possible) existence of a physical process which can function as what we call the 'core' of a clock. In particular, we suggest that in order to make the $t \leftrightarrow$ time interpretation at a specific cosmological 'epoch', the physical process acting as the core of a clock should 1) have a well-defined duration which is sufficiently fine-grained to 'time' the epoch in question; and 2) be a process which could conceivably take place among the material constituents available in the universe at this epoch. Consequently, we shall devote a large part of the investigation to an examination of what such a core of a clock could be in the context of early universe cosmology. Our analysis suggests that the physical basis of time – or, more precisely, the time scale – becomes rather uncertain already when the FLRW metric is extrapolated back to $\sim 10^{-11}$ seconds. This could indicate that the time scale concept becomes insufficiently founded (or at least highly speculative) already ~ 30 orders of magnitude 'before' the Planck time is reached.

Our reasoning is based on the observation that we shall be (almost) unable to find scale-setting physical processes (cores of clocks) in the 'desert' above the Higgs phase transition – if the physics is based on an extrapolation of what is considered well-known and established physics in the form of the standard model of the electroweak and strong forces. In order to provide a physical foundation for the time scale above the Higgs transition we will have to base it on speculative new physics, and the time scale linked to this new physics will be speculative as well. Moreover, the in-principle existence of extended physical objects which can function as rods (which appear to be a prerequisite to set up the coordinate frame in cosmology, see section 3) becomes gradually less clear: Above the quark-hadron phase transition (at $t \sim 10^{-5}$ seconds) there are roughly no bound systems left, and the notion of length and time scales becomes even more ill-defined above the Higgs phase transition (at $t \sim 10^{-11}$ seconds) if those scales are to be constructed out of the by-then available massless material constituents.

The structure of the paper is as follows. In section 2 we discuss the meaning of time, and suggest that the well-defined use of time in both ordinary practical language and physics is necessarily related to the notion of a physical process which can function as a clock or a core of a clock. In section 3 we briefly investigate the time and clock concepts as they are employed in cosmology and the underlying theories of relativity.[2] In section 4 we examine the possible physical underpinnings for (cores of) clocks in the early universe. Results from this analysis are employed in section 5 where we discuss how the identification of (cores of) clocks becomes progressively more problematic as we go to smaller t-values in the FLRW metric. A summary and some concluding remarks are offered in a final section.

2   The meaning of time

The concepts of time and space are so fundamentally interwoven in our daily and scientific language that it is difficult to extract an unambiguous meaning (or definition) of these concepts. In the present manuscript we shall restrict our investigation to an examination of the time concept in the realm of modern cosmology in which our ordinary language (and its refinements in modern physics theory) is pressed to the utmost. In this section we try to establish a few general points on the meaning of time, which are relevant to cosmology.[3]

It has been known at least since St. Augustine that it is difficult, if not impossible, to give a *reductive* definition of time in terms of other concepts that are themselves independent of time (see e.g. Gale 1968, pp. 3-4). For instance, operationalism, 'time is what a clock measures', is ruled out as a reductive definition, since one cannot specify what a clock (or a measurement) means without invoking temporal notions. Also it seems difficult to provide a meaning of time via a referential theory of meaning, assuming e.g. that 'time is (or means) whatever it corresponds to in reality', since one cannot point to or specify what this referent might be (or at least, as we shall discuss below, it is difficult to do this unless the referent somehow involves clocks). The difficulties in providing a meaning (or definition) of time point to the common intuition that time is a fundamental concept, i.e. it is not possible to define the concept of time reductively.

Even though we cannot provide a reductive definition of time, we are nevertheless able to use, and understand, the concept of time in a non-ambiguous manner

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[2]The present manuscript focuses on the classical space-time description of the universe and the possibility to identify physical processes which can function as (cores of) clocks. Although time is a classical parameter also in quantum physics, aspects of the problem about time which are directly related to the quantum nature of the physical constituents of the universe will be examined in a separate investigation, see Rugh and Zinkernagel (2008).

[3]In this manuscript we are exclusively concerned with the meaning of time in physics and what may be called ordinary practical language, e.g. we do not address psychological, poetic or religious uses of the concept. The body of literature dealing with the concept of time in general is rather large. J.T. Fraser has estimated that the number of potentially relevant references (books and articles from 1900 to 1980) for a systematic study of time is around 65,000. (cf. Fraser and Soulsby, "The literature of time", pp. 142 - 144 in Whitrow (2003)).

in a variety of situations in both ordinary practical language and in physics. This suggests that the meaning of time might be extracted from some common characteristic feature (or features) of the use of the time concept in these situations.[4] In both ordinary language and in physics we use expressions such as "this event takes a certain amount of time", "this event occurred such and such amount of time ago", or "this event is earlier/later than that event". In these expressions, and in a multitude of other expressions involving time, the meaning is usually non-ambiguous since the 'time of the event' or the 'amount of time' can be identified by referring to some physical process which can function as a clock (or, a 'core' of a clock, see below). Indeed, as far as we can see, these (and similar) expressions involving time could not be given an unambiguous meaning *except* by referring to some physical process. For instance, how should "3 years" be understood in a sentence like "3 years passed, yet no physical process took place (or, counterfactually, could have taken place) at all"? If reference to physical (clock) processes is not presupposed then how is such a statement to be distinguished from a similar one involving 4, 5 or any other number of years? As indicated above, however, (physical processes which can function as or in) clocks cannot define time reductively since any analysis of what a clock is (and does) will at some point involve temporal notions. We therefore venture to formulate the following time-clock relation – which is an attempt to extract a thesis concerning the correct use of the time concept from ordinary practical language and physics:

> **The time-clock relation:** There is a logical (or conceptually necessary) relation between 'time' and 'a physical process which can function as a clock (or a core of a clock)' in the sense that we cannot – in a well-defined way – use either of these concepts without referring to (or presupposing) the other.

We denote this relation 'time-clock' in part to avoid the more cumbersome 'time-physical process which can function as a clock (or a core of a clock)', and in part to follow the standard practice in cosmology textbooks where time is associated with so-called 'standard clocks' (see section 2.3) – usually without any specification of what such standard clocks are. In accordance with this labelling, we shall in the following often use 'clock' as shorthand for 'physical process which can function as a (core of a) clock'.

What is a core of a clock? According to a common conception, an ordinary clock consists of a system which undergoes a physical process, as well as some kind of counter (e.g. a clock dial) which registers increments of time.[5] Note that a

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[4]Of course, 'meaning' is a contentious philosophical notion. We are here assuming, inspired also by ideas in Zinkernagel (1962), that a relevant alternative to operational and referential meaning theories for time is a version of Wittgenstein's idea that the meaning of a concept is somehow given by its use.

[5]The second component of a(n) (ordinary) clock, that of an irreversible registration with a counter, connects the discussion of the concept of time with the existence of 'an arrow of time' (an issue we shall not pursue here).

change in the counter (e.g. a displacement of the hands in a grandfather clock) is itself a physical process which can be said to function as a clock – as opposed to the swinging pendulum inside the grandfather clock which functions as the core of the clock.[6] Since no real functioning clocks (with counters or dials) are available in the early universe we shall in the following focus on physical processes which can function as cores of clocks. As we shall discuss below, the requirements that a physical process must satisfy in order to function as a core of a clock will depend on which characteristic of time – temporal order or temporal scale – is in question.[7]

The time-clock relation does not imply that physical processes are more fundamental than time but is rather a thesis stating that time and physical processes which can function as (cores of) clocks cannot be defined independently of one another. Although formulated as a relation between concepts, the time-clock relation reaches beyond the conceptual level.[8] For instance, the relation is also meant to capture the idea that the use of the time concept, e.g. as in the above example with "3 years", refers to (actually or counterfactually) existing physical processes. In this sense the use of the time concept presupposes both the possible (actual or counterfactual) *existence* and the *concept* of physical processes (see also the discussion in Zinkernagel 2008).

2.1 Implicit definition of time via laws of nature

By possible physical processes we shall understand processes which are allowed by the laws of nature. This connects the time-clock relation with the idea of an implicit definition of time via laws. To appreciate this connection, we first note that although laws of nature (which are typically evolutionary laws with respect to a time parameter t) can refine, or make precise, our pre-theoretical notion of time, they cannot provide a *reductive* definition of time in terms of other concepts appearing in the laws, since at least some of these concepts will themselves depend on – and have to be specified as a function of – time; see below for an example. More importantly, the idea of implicitly defining time via laws is in conformity with the time-clock relation since, in our assessment, any such definition must make use of actual or counterfactual clocks – or, more precisely, of some possible physical process (or class of processes) which can function as (clocks or) cores of clocks.

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[6]Either one of these processes (hand-displacement and pendulum-swing) may serve to make certain temporal statements well-defined, hence the formulation '...clock or core of a clock' in the time-clock relation.

[7]It is standard to distinguish between order and metrical aspects of time, cf. e.g. Newton-Smith (1980). With a temporal order one may speak of some event being before or after another event (however, as we do not discuss the arrow of time, our notion of time order refers not to the direction of time but merely to the idea that two events are temporally separated – that is, either before or after one another). The notion of a temporal metric allows for addressing quantitatively how much time separates two events. In this manuscript we shall be particularly interested in the time *scale* (a metrical aspect of time) which assigns specific values to the duration of time intervals in some chosen unit.

[8]The notion of logical relations between concepts (which in formal logic are relations between concepts like 'not', 'and', 'both-and' etc.) is inspired by P. Zinkernagel (1962 and 2001).

Consider for instance Poincaré's analysis of the link between the time concept and the mathematical structure of the natural laws (1905, p.215): "So that the definition implicitly adopted by the astronomers may be summed up thus: time should be so defined that the equations of mechanics may be as simple as possible".[9] This idea of an implicit definition of time addresses not what time as such is (again, it is not a reductive definition) but rather *which* time parameter is the most adequate (or, in Poincaré's terminology, most convenient) for the physical situation in question. Poincaré discussed what later became known as ephemeris time: Observations of the positions of the bodies in the solar system (in terms of the time standard provided by the earth's rotation) lead to discrepancies with the positions of these bodies as predicted by Newtonian mechanics – and ephemeris time is the time standard which minimizes the discrepancies, and thus makes Newton's laws come out right (there will, however, be residual effects e.g. due to general relativistic corrections and limited observational accuracy; for more details see e.g. Barbour (1999) p.106, and Audoin and Guinot (2001) p.46 ff). A simpler example is mentioned by Misner, Thorne and Wheeler (1973, p. 26): In the case of moving free particles, the time parameter should be chosen, in accordance with Newton's first law, so as to make the tracks of the particles through a local region of spacetime look straight (that is, the particles should traverse equal distance in equal times) – any other choice of time will make the motion look complicated (the tracks will be curved).

The important point for both ephemeris time and free particle motion is that in either case the implicit definition of time is made by appealing not only to the laws but also to some physical clock system (or class of physical clock systems): the solar system (an actual clock) in the case of ephemeris time, and free particles (an ideal, and hence counterfactual, clock) in Misner, Thorne and Wheeler's case.[10]

The same conclusion can be reached if we attempt to make the implicit definition of time via laws 'explicit' by expressing time as a function of the other physical quantities appearing in the laws. Consider, for instance, how the time parameter t could be extracted from the 'evolution' of the other physical quantities which appear in Newton's second law, $\boldsymbol{F} = m(d^2\boldsymbol{r}/dt^2)$. Given two sets of values of $\boldsymbol{F}$ and $\boldsymbol{r}$ (assuming m is constant) one might attempt to determine the time (duration) it takes for the system to get from $(\boldsymbol{F}_1, \boldsymbol{r}_1)$ to $(\boldsymbol{F}_2, \boldsymbol{r}_2)$ by inverting and integrating (twice) Newton's law and solve for t. However, in order to perform the integration and get a definite value, one would have to specify (a further initial condition, e.g. the initial velocity $\boldsymbol{v}_1$ and) the force field $\boldsymbol{F}$ as a function of $\boldsymbol{r}$ and t. Otherwise,

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[9]The idea of implicitly defining time via simplicity considerations of the dynamical equations in question is also discussed in Brown (2006, p. 92-93).

[10]Note that although there is a difference between realistic (more or less accurate) clocks and perfect (or ideal) clocks, this difference is not important for the time-clock relation: perfect clocks are never realized but we may still refer to such clocks as idealizations over real clocks, and we can, at least in principle, estimate the inaccuracy of any clock using the laws of nature if we know about the imprecision involved (this is e.g. how we determine that even the best atomic clocks are slightly imperfect). Thus, as far as the time-clock relation goes, any clock can be used to make time a well-defined concept. For instance, it is a perfectly meaningful statement to say "according to my old wrist-watch, the football match lasted only 88 minutes". Of course, in physics and astronomy one is often after good (close to perfect) clocks, since these are the most useful ones.

one cannot determine the trajectory connecting $(\boldsymbol{F}_1, \boldsymbol{r}_1)$ and $(\boldsymbol{F}_2, \boldsymbol{r}_2)$ and thus the time it takes for the system to get from one state to the other. This not only reaffirms that one needs a notion of time from the outset (so that time cannot be reductively defined by the law), but the resulting picture is also in conformity with the time-clock relation: Specifying the force field acting on the mass in question is equivalent to specifying a physical system (or class of systems) — such as a free particle, $F = 0$, a simple harmonic oscillator, $F = kr$, or a simple pendulum in a constant gravitational field, $F = mg \sin \phi$ — and the process bringing the system from $(\boldsymbol{F}_1, \boldsymbol{r}_1)$ to $(\boldsymbol{F}_2, \boldsymbol{r}_2)$ is a physical process which can function as the core of a clock. Also in this case, then, the 'implicit' definition of time is made by appealing to possible physical (clock) systems.

With this clarification of the close connection between the time-clock relation and natural laws in mind, we can now specify what we take to be implied by the statement 'time has a well-defined use'. According to the time-clock relation, it involves a reference to some physical process (a process in conformity with physical laws). This can also be expressed by saying that the well-defined use of time requires that the process referred to has a physical basis. In the following, we shall formulate this idea as the assertion that a well-defined use of time requires that time has a physical basis. More specifically, for the time concept to have a physical basis we shall require one of two things (see also below and section 4) – depending on whether it is the time scale or the time order (or both) which is in question: The time scale has a physical basis if some actual or possible physical process has a duration shorter or equal to the time interval in question.[11] The time order, i.e. that an event A is before (or after) an event B, has a physical basis if some actual or possible physical process can take place between A and B. Of course, in ordinary practical language and in physics we, in general, need a physical basis (and a well-defined use) of both the time scale and the time order.

2.2   The time-clock relation and relationism

Since clocks involve change, the time-clock relation is in conformity with a version of relationism according to which time is dependent on change. This kind of relationism is in the tradition of Aristotle who argued in his *Physics* (350 B.C.) that time is the measure (or number) of motion, and that time and motion define each other. Also Leibniz argued that time must be understood in relation to matter and motion: "Space and matter differ, as time and motion. However, these things, though different, are inseparable" (Leibniz 1716, cf. Alexander (1956, p. 78)). Nevertheless, the relationism implied by the time-clock relation diverges from both Aristotle's and Leibniz's versions. First, as already noted, the time-clock relation allows counterfactual clocks (or motion) and is thus at odds with Aristotle's relationism insofar as his version refers exclusively to actual (measured) motion. Second, we do not argue, as

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[11]This means that we would consider a time interval of, say, 10^{-100} seconds a purely mathematical abstraction (with no physical basis) insofar as no physical process (in conformity with known laws) which could exemplify such an interval is thinkable.

did Leibniz, for a reductive relationism – i.e. that time can be reduced to temporal relations between events. To assume that time is just temporal (before, after, and simultaneous) relations between events leaves open what exactly a *temporal* relation is (or what is temporal about the relations). We doubt that there is any way to explain what 'temporal' (and 'before', 'after', and 'simultaneous') means without invoking the notion of time itself.[12] If this doubt is justified such a reductive or eliminative analysis of time cannot work.

The non-reductive aspect of the relationism defended here sets us apart from some modern relationists who otherwise also argue for the necessity of clocks in order to give meaning to (at least the metrical aspects of) time. Thus, for instance, Grünbaum (1977) advocates a relationism in the context of general relativity which holds that "[i]n a *non*empty, metrically structured space-time, metric standards [like rods and clocks] external to this space-time do play an ontologically constitutive role in its very metricality or possession of any metric structure at all, and the gravitational field of *empty* space-times are devoid of *geometrical* physical significance..." (p. 341, emphasis in original). Another example, inspired by Leibniz and with a view to quantum gravity, is Smolin (1999, p. 238) who argues that "...at least at the present time, the only useful concept of time that exists in general relativity, in the cosmological context, is ... the time as measured by a physical clock that is part of the universe and is dynamically coupled to the rest of it". A related example is Barbour (1999). If one abstracts from Barbour's (quantum gravity inspired) goal of eliminating time altogether, his relationism has similarities to what we are defending, cf. e.g. "...time is told by matter – something has to move if we are to speak of time" (1999, p. 100).[13]

We are aware that the time-clock relation, and the relationism accompanying it, is likely to be rejected by substantivalists (and presumably by some relationists as well).[14] However, we take it be a difficult challenge for substantivalists and other

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[12]For instance we doubt that temporal relations can, as suggested e.g. by Leibniz, Reichenbach, and Grünbaum, be reduced to causal relations in a non-circular manner.

[13]Barbour's advocacy of relationism in classical mechanics involves the derivation of the time metric from considering the dynamical system in question in a way similar to the way ephemeris time is defined (Barbour 1999, pp. 104 ff.). And, as Barbour notes (1989, p.181) "...ephemeris time is only abstract in the sense that it is not realized by any one particular motion but is concrete in the sense that it must be determined empirically from actually observed motions". This might well be an indication that Barbour would agree with the point made above, viz. that the definition of ephemeris time, and other implicit definitions of time, appeals both to (Newton's) laws and to a specific physical (clock) system.

[14]In general, substantivalists hold that (space-)time exists independently of material things, see e.g. Hoefer (1996) for a classification and discussion of various versions of substantivalism. In light of the theories of relativity, with their notion of four dimensional space-time, the debate between relationism and substantivalism is mostly about *both* space and time. In this manuscript we shall mainly focus on time, and we do not claim that our considerations about time and clocks hold analogously for space and rods. For instance, while we would argue that physical (and metrical) space does need material systems which could function as rods to be interpreted as such, we shall not here question the space concept *far away* from us (or in the 'empty space' inside a spatially extended material box) whereas we do try to question (see below) the time concept *long time ago* (in the 'very early' universe).

critics of the time-clock relation to account for the meaning, or well-defined use, of time independently of clocks. For, in our view, such an alternative account of time ought to be closely related to our usual notion of time in ordinary practical language and physics (which does depend on clocks) – otherwise why call it time at all?

For instance, a manifold substantivalist (who holds that space-time is exhaustively described by a four dimensional manifold, see e.g. Earman and Norton (1987)) will presumably hold that the meaning of time can be inferred from, or identified with, a mathematical structure (the manifold). In our assessment, however, while time can be (and in physics always is) represented mathematically, it would be a mistake to think that there is nothing more to time than a mathematical structure. The fact that our usual notion of time can be associated with a formal (mathematical) structure originates in time being related to physical (clock) systems, e.g. as when we count the number of sunrises and represent the amount by natural numbers. As mentioned above, it is this association to physical systems which is used to give unambiguous meaning to statements involving time e.g. statements about the temporal separation between events. In any case, as noted e.g. by Hoefer (1996, p. 11) there is nothing inherent in a (mathematical) manifold which distinguishes space and time.

The substantivalist could more plausibly hold that time is defined as a part of the space-time 'container' constituted by a manifold plus a metric, in which physical objects and processes are (or may be) embedded in accordance with physical laws.[15] If this view is understood as implying that time is implicitly defined by laws of nature it is not in conflict with the time-clock relation since (i) as discussed above, implicit definitions of time rely on possible physical processes; and (ii) the time-clock relation refers to actual *or* counterfactual physical processes in conformity with the laws of nature. It might seem that the inclusion of the metric, subject to Einstein's field equations, in what is called space-time could give a physical basis for both the time order *and* the time scale independently of any matter content or material processes (e.g. by referring to processes involving only gravitational waves). However, the manifold and the metric (and the vacuum Einstein's equations) by themselves cannot provide a time (or length) scale since neither c nor the combination of c and G sets a time (or length) scale. This means that unless the material content, represented by $T_{\mu\nu}$ on the right-hand side of Einstein's equations, provides a physical scale (see section 4) there is no physical basis for a time scale. Essentially the same point was made already by Eddington ((1939, p. 76), see also Whitrow (1980, p. 281)):

> ...relativity theory has to go outside its own borders to obtain the definition of length, without which it cannot begin. It is the microscopic structure of matter which introduces a definite scale of things.

As we shall see, the (micro-) physical laws operative in the very early universe (and thus the associated energy-momentum tensor $T_{\mu\nu}$) may not be able to provide the

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[15]This corresponds to what Hoefer (1996) calls manifold plus metric substantivalism or metric field substantivalism (the distinction between these substantivalisms is important for responses to the famous hole argument, but makes no difference for our discussion).

required physical scales. If this is the case then one can at most address the question of time *order* and not time *duration* for this 'epoch' (see also below).

2.3 The role of clocks in cosmology

The time-clock relation is in conformity with the use of time in cosmology although cosmologists often formulate themselves in operationalist terms – that is, invoking observers measuring on factual clocks.[16] For instance, Peacock (1999, p. 67) writes concerning the Friedmann-Lemaitre-Robertson-Walker (FLRW) model, which is the standard cosmological model (and the one we discuss in the present manuscript):

> We can define a global time coordinate t, which is the time measured by clocks of these observers – i.e. t is the proper time measured by an observer at rest with respect to the local matter distribution.

While this reference to clocks (or 'standard' clocks) carried by comoving observers is widely made in cosmology textbooks, there is usually no discussion concerning the origin and nature of these clocks. Part of the motivation for the present investigation is to provide a discussion of this kind.

Whereas cosmologists often refer to clocks as sketched above, they also define cosmic time 'implicitly' by the specific cosmological model employed to describe the universe (e.g. through the relation between time and the scale factor, see section 4). However, in accordance with the discussion above, a definition of cosmic time via the cosmological model requires that the time concept of the model can be given a physical basis. Moreover, a backward extrapolation of the time concept of the model requires that the model itself can be given a physical basis.[17]

The FLRW model has a built-in t concept which, as a mathematical study, can be extrapolated back arbitrarily close to zero. The question is whether the mathematical parameter t can be given the physical interpretation of time for *all* (positive) values of t, or only for some (more) restricted subset of the t-interval. The $t \leftrightarrow$ time interpretation in the FLRW model can be made at present since the

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[16]Our view on the time concept represents a departure from operationalism in several ways: Apart from the point that clocks cannot define time reductively (since clocks and measurements depend on the time concept), we allow reference to counterfactual clocks; we attempt to construct the *cores* of clocks out of available physics, but do not require that this core should be associated with a counter mechanism that could transform it into a real functioning clock; and we do not require the existence of observers and actual measurements.

[17]The question of what it means for a model to have a physical basis connects to a vast literature in the philosophy of science (for an introduction to this literature, see e.g. Frigg and Hartman 2006). We take it that for a cosmological model to have a physical basis involves, as a minimum, that the (physical) conditions to set up the model are at least approximately satisfied in the domain in which the model is applied. In fact, as we shall discuss further in section 3, a more basic requirement for a cosmological model to have a physical basis is that the concepts involved in the model (e.g. concepts like "homogeneity", "particle trajectory" and, of course, "time") are physically grounded in the domain in which the model is applied. Otherwise, one could not, in a well-defined way, pose the question (let alone determine the answer) of whether or not the physical conditions to set up the model are satisfied.

physical conditions for setting up the FLRW model are (approximately) satisfied at present (section 3) and since the t parameter in the model can be correlated to physical (clock) processes. For instance, clocks on earth measure time intervals approximately in accordance with t intervals in the FLRW model since earth clocks are approximately at rest in the comoving frame (see section 3). Given the $t \leftrightarrow$ time interpretation of the FLRW model at present, one might then imagine extrapolating the physical interpretation of t 'all the way back in t', or at least sixty orders of magnitude from the present back to the Planck scale. In this way, the fact that the FLRW model has a physical basis in some t parameter range is used to give meaning to time (via this model) in other t intervals.

However, since the procedure in question involves the extrapolation of the FLRW model and its time concept it requires in our view that the physical basis of time in the model and, more generally, the physical conditions needed to set up the model, are not invalidated along this extrapolation. As we shall see, a major problem is that length and time scale setting physical processes permitted by physical laws at present, may not be allowed in a much earlier cosmic epoch. Note in this connection that the laws of physics are often assumed to be invariant under translations in space and time (see e.g. Ellis 2006). Hence one might think that if the time concept has a physical basis in one (temporal) domain then it ought to have it in all domains (modulo Planck scale considerations). In the cosmological context however this time translation invariance of physical laws is constrained since cosmological phase transitions may change the *effective* laws of microphysics (in this way, one may speak of an evolution in the laws of nature, see e.g. Schweber 1997).[18] In particular, the physical basis for the time scale may break down in the very early universe as a result of phase transitions, cf. section 5.

The relevance of taking into consideration the physical basis of the FLRW model and its time concept is exemplified by the widely accepted expectation that the model cannot be extrapolated below Planck scales and, accordingly, that the $t \leftrightarrow$ time interpretation cannot be made for t values below 10^{-43} seconds.[19] This illustrates that a physical condition (namely that quantum effects may be neglected) can imply a limitation for the $t \leftrightarrow$ time interpretation. But if it is accepted that

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[18]Note that since the concept of time may be seen to be implicitly defined by the laws of physics (section 2.1) it is difficult to say what we could mean by 'time translation invariance of the laws of physics'. With respect to which notion of time (living "outside" the realm of physical laws) should this time translation invariance of the laws of physics be addressed? There is, however, a (widely accepted) sense in which the effective laws change in cosmic time in the early universe ($\rightarrow$ nuclear age $\rightarrow$ atomic physics age $\rightarrow$ etc.) as the temperature decreases. This lack of time translation invariance of the effective laws should be addressed with respect to the t parameter in the FLRW model. As we shall see, it is precisely these effective laws which must be used to provide a physical basis for (in particular, the scale of) the t parameter in the FLRW model, and thus these laws which allow the interpretation of t as (metrical) time.

[19]The Planck scale limitation is inferred from the expectation that the space-time metric (because of quantum effects) fluctuates increasingly as the Planck scale is approached, and thus the (classical) time concept is gradually rendered invalid. This invalidation presumably affects both the order and the metrical aspect of time insofar as no physical process can be clearly distinguished 'before' the Planck scale (cf. the problem of time in quantum gravity).

there is at least *one* physical condition which must be satisfied in order to trust the backward extrapolation of the FLRW model and its time concept, it appears reasonable to require that also *other* physical conditions (which are necessary to set up the FLRW model) should be satisfied during this extrapolation.[20]

The idea of examining the $t \leftrightarrow$ time interpretation in cosmology appears to be in the spirit of the discussion in Misner, Thorne and Wheeler (1973) (henceforth MTW) concerning how present physical scales might be extrapolated into the past. In connection with the question of a singularity occurring at a finite past proper time they write (p. 814):

> "The cosmological singularity occurred ten thousand million years ago." In this statement take time to mean the proper time along the world line of the solar system, ephemeris time. Then the statement would have a most direct physical significance if it meant that the Earth had completed 10^{10} orbits about the sun since the beginning of the universe. But proper time is not that closely tied to actual physical phenomena. The statement merely implies that those 5×10^9 orbits which the earth may have actually accomplished give a standard of time which is to be *extrapolated in prescribed ways*, thus giving theoretical meaning to the other 5×10^9 which are asserted to have preceded the formation of the solar system. [our emphasis]

But MTW does not explain what these "prescribed ways" are. We have suggested above that such backward extrapolation of physical scales makes sense (has a physical basis) only insofar (i) it is still possible to identify physical processes which may function as (the cores of) clocks; and (ii) these clocks (based on the available physics) should set a sufficiently fine-grained physical scale in order to specify the time of the epoch. Perhaps MTW would have agreed, for they note (p. 814) that even with better (and earlier) clocks there will always be a residual problem concerning the physical notion of time:

> Each actual clock has its "ticks" discounted by a suitable factor - $3 * 10^7$ seconds per orbit from the Earth-sun system, $1.1 * 10^{-10}$ seconds per oscillation for the Cesium transition, etc. Since no single clock (because of its finite size and strength) is conceivable all the way back to the singularity, a statement about the proper time since the singularity involves the concept of an infinite sequence of successively smaller and sturdier clocks with their ticks then discounted and added. [...] ...finiteness [of the age of the universe] would be judged by counting the number of discrete ticks on *realizable clocks*, not by accessing the weight of unrealizable mathematical abstractions.

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[20]We note that – except for the space-time singularity itself – there are no internal contradictions in the *mathematics* of the FLRW model (or classical general relativity) which suggests that this model should become invalid at some point, e.g. at the Planck scale.

This quote seems to imply that the progressively more extreme physical conditions, as we extrapolate the FLRW model backwards, demand a succession of gradually more fine-grained clocks to give meaning to (provide a physical basis of) the time of each of the epochs.[21] In the same spirit, our view is that a minimal requirement for interpreting t as time (with a scale) is that it must be possible to find physical processes (the cores of clocks) with a specified duration in the physics envisaged in the various epochs of cosmic history.[22] In section 4 and 5, we shall investigate in more detail how far back in cosmic time this criterion can be satisfied.

In general, the duration of the physical process functioning as the core of a clock will specify a standard of time but, as we shall see, there might be epochs where it is only possible to speak of 'scale free' clocks, which can order events but not determine how much time there is in between them. We note that if a point is reached in the backward extrapolation of the FLRW model where no 'scale clocks', but only non-metrical 'order clocks' could exist, one would lose all handle on how close we are to the singularity. Since modern cosmology makes extensive use of specific times, e.g. to locate the cosmological phase transitions, we shall in the following focus on physical clocks which can set a time scale. One may *speculate* on the existence of (scale-setting, i.e. metrical) clocks based on ideas beyond presently known physics. However, if such speculative clocks are invoked to give meaning to some epoch in cosmology, it should be admitted that the time of this 'epoch' becomes as speculative as the contemplated physics of these clocks.

3   Time in Relativity and FLRW cosmology

The conceptual apparatus of standard cosmology (and its interpretation) originates within the framework of general relativity in which various conceptions of time are at play. Rovelli (1995), for instance, distinguishes between coordinate time (which can be rescaled arbitrarily), proper time ($d\tau = ds/c = 1/c\sqrt{g_{\mu\nu}dx^\mu dx^\nu}$), and clock time (which is what is measured by a more or less realistic clock). By itself, coordinate 'time' has no physical content so one might argue that it should not even be called time but rather just t. Coordinate 'time' is however identified with proper time in some models of GR (in which a 'gauge' fixing has constrained the choice of coordinate

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[21]For instance, no stable Cesium atoms – let alone real functioning Cesium clocks – can exist before the time of decoupling of radiation and matter, about 380,000 years after the big bang.

[22]As noted earlier, the time-clock relation is also satisfied by counterfactual clocks, that is, even if no actual physical (clock) process correlated with t took place in an interval of cosmic time, it is sufficient if some physical process *could possibly* (consistent with the available physics) have taken place. For our purposes in this paper this criterion is sufficient since, as we shall argue, both actual and counterfactual clocks (which can set definite time scales e.g. in the unit of seconds) may be ruled out by the physics describing the very early universe. If one were to contemplate a possible world with altogether different laws than in our universe, allowing for different clocks – "counterlegal" from the point of view of our universe – then there might be no problem about very early times (thanks to Jeremy Butterfield for bringing this possibility to our attention). On the other hand, the relevance of this is not obvious as it is not clear whether or how the t (time) coordinates in the two worlds would be related.

system, as in FLRW cosmology – see below). And proper time does deserve its name (time), at least when it is associated with the time of a standard clock, cf. also MTW (1973, p. 814):

> ...proper time is the most physically significant, most physical real time we know. It corresponds to the ticking of physical clocks and measures the natural rhythms of actual events.

3.1 The necessity of rods and clocks in relativity

The indispensability of (rods and) clocks for a physical interpretation of relativity theory is not a novel idea. As is well known, Einstein initiated the theory in a positivistic spirit which implied an operational meaning criterion e.g. for the definition of time in terms of what clocks measure. But even if Einstein subscribed less to a positivistic philosophy over the years (Ryckman 2001), he kept referring to the role of measuring rods and clocks in order to give physical meaning to the coordinates in special relativity. By contrast, it is often emphasized that there is no physical meaning to the coordinates in general relativity (e.g Rovelli 2001).[23] However, as we argue throughout this manuscript, the possible existence of (the core of) rods and clocks – i.e. length and time scale setting physical objects or processes from microphysics – are in any case indispensable in GR (and the FLRW model) at least in order to provide a physical foundation for the scales of length and time.

The necessity of *material* rods and clocks (external to GR itself) can be, and has been, questioned e.g. by referring to the 'geometrodynamical clock' developed by Marzke and Wheeler (see e.g. MTW p. 397-399) which does not depend on the structure of matter (see also Ryckman 2001 for references concerning the limitations of the concept of a rigid rod in general relativity). Thus, MTW writes (p. 396): "In principle, one can build ideal rods and clocks from the geodesic world lines of freely falling test particles and photons. [...] In other words, spacetime has its own rods and clocks built into itself, even when matter and nongravitational fields are absent!". The geometrodynamical clock is built out of two 'mirrors' moving in parallel between which a pulse of light is bouncing back and forth. The mirrors can be any system absorbing and re-emitting light. In the cosmological context, however, there are at least two problems in using such clocks as a physical underpinning for the FLRW reference frame (for a general discussion and critique of the Marzke-Wheeler construction, see Grünbaum 1973, p. 730 ff.). First, mirror systems moving in parallel are presumably difficult to envisage (even in principle) from the available constituents in the early universe. Second, and more importantly, since the electromagnetic theory of light is scale invariant such light clocks cannot set a scale which

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[23]Einstein's own remarks on time in GR are somewhat obscure, see e.g. Einstein (1920), chap. 28, where he suggests defining time in terms of 'Dali like' clocks attached to deformable non-rigid reference bodies (Einstein calls them "reference-molluscs"). While Einstein suggests that the laws of motion for these clocks can be anything, he does demand "...that the 'readings' which are observed simultaneously on adjacent clocks (in space) differ from each other by an indefinitely small amount" (Einstein 1920, p. 99). But this seems possible only if the clocks work normally (as in special relativity) and in this sense are standard clocks.

can provide a physical basis for specific times in cosmology. As we shall discuss later on, there might be 'epochs' in the early universe in which it is no longer possible to identify physical systems (among the envisaged constituents) which may function as (the core of) rods and clocks.[24]

3.2 Time in big bang cosmology

After the above brief remarks about time in relativity, we now turn to cosmology. Time depends on the chosen reference frame already within the limited set of coordinate transformations allowed in special relativity. Thus, it is necessary to specify a privileged coordinate frame in cosmology if a conception of cosmological time (defined throughout the universe) is to be found. The large scale space-time structure of the cosmological standard model is based on the FLRW line element. Apart from a discussion on the exact choice of the coordinates, the form of this quantity can be derived from two assumptions, namely

1. Weyl's postulate. The world lines of galaxies (or 'fundamental particles') form a bundle of non-intersecting geodesics orthogonal to a series of spacelike hypersurfaces. This series of hypersurfaces allows for a common cosmic time and the spacelike hypersurfaces are the surfaces of simultaneity with respect to this cosmic time (see below).[25]

2. The cosmological principle. This states that the universe, on large scales, is spatially homogeneous and spatially isotropic.[26]

The idea of the Weyl postulate is to build up a comoving reference frame in which the constituents of the universe are at rest (on average) relative to the comoving coordinates, cf. Narlikar (2002, p. 107 ff.) (for a historical account of Weyl's postulate, or principle, see North (1990, p. 100 ff.)). The trajectories $x_i = $ constant of the constituents are freely falling geodesics, and the requirement that the geodesics be orthogonal to the spacelike hypersurfaces translates into the requirement $g_{0i} = 0$,

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[24]In particular, we shall see in section 5 that electromagnetic theory including sources (e.g. electrons) – as well as the other constituents of the standard model of particle physics – is scale invariant above the electroweak phase transition. This implies, for instance, that not even the test particles (the mirrors) of the Marzke-Wheeler geometrodynamical clock are able to set a length scale or a time scale above ('before') this phase transition.

[25]We note that the while the Weyl principle and the cosmological principle allow for the possibility to set up a *global* cosmic time, the implementation of these principles can only be motivated physically if we already have a physical foundation for the concepts of 'space' and 'time' *locally* – otherwise we cannot apply concepts like "spacelike", "spatially homogeneous", "spatially isotropic", which appear in the definitions of Weyl's principle and the cosmological principle.

[26]The requirement of 'isotropy' is to be understood relative to the privileged reference frame outlined below (see also Weinberg (1972, p. 410) and MTW (1973, p. 714)). Some cosmologists (e.g. Pietronero and Labini (2004)) doubt whether observations actually justify the homogeneity assumption at the largest observed scales (~ 800 Mpc). In the present manuscript, however, we shall confine our discussion to the cosmological standard model, and leave out possible alternatives, see e.g., Narlikar (2002) and López-Corredoira (2003) and references therein.

which (globally) resolves the space-time into space and time (a 3+1 split). We have $g_{00} = 1$ if we choose the time coordinate t so that it corresponds to proper time ($dt = ds/c$) along the lines of constant x_i (see Robertson 1933), i.e. t corresponds to clock time for a standard clock at rest in the comoving coordinate system. The metric is thereby resolved into $ds^2 = c^2 dt^2 - g_{ij}(x, t) dx^i dx^j$.[27] The spatial part of this metric is then simplified considerably by application of the cosmological principle (see below).

The empirical adequacy of both the Weyl postulate and the cosmological principle depends on the physical constituents of the universe.[28] We shall later observe that as we go backwards in time it may become increasingly more difficult to satisfy, or *even formulate*, these principles as physical principles since the nature of the physical constituents is changing from galaxies, to relativistic gas particles, and to entirely massless particles moving with velocity c.[29] Correspondingly, as we shall see, the effective physical laws describing the constituents of the universe change as the temperature rises and eventually become scale invariant above the electroweak phase transition. This makes it difficult to even formulate e.g. the cosmological principle (let alone decide whether it is satisfied): If an epoch is reached in which the fundamental constituents become massless, so that a local scale invariance (conformal invariance) of the microphysics is obtained (see section 5.4), it would seem that the concept of homogeneity lacks a physical basis. For homogeneity rests on the idea of (constant) energy density in different spatial points and (constant) energy density is not an invariant concept under local scale transformations.[30] On top of this, the physical basis of the Weyl postulate (e.g. "non-intersecting world lines of fundamental particles") appears questionable if some period in cosmic history is reached where the 'fundamental particles' are described by wave-functions $\psi(x, t)$

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[27]As noted e.g. by Coles (2001, p. 313), this synchronous coordinate system, $g_{0\mu} = (1, 0, 0, 0)$, is "...the most commonly used way of defining time in cosmology. Other ways are, however, possible and indeed useful in other circumstances."

[28]For instance, Robertson (1933) noted that the reintroduction in cosmology of a significant simultaneity (in the comoving coordinate system) implied by Weyl's postulate is permissible since observations support the idea that galaxies (in average) are moving away from each other with a mean motion which represents the actual motion to within relatively small and unsystematic deviations.

[29]Narlikar (2002) comments (p. 131) that for a gas of relativistic particles where one has random movement "...the Weyl postulate is not satisfied for a typical particle, but it may still be applied to the center of mass of a typical spherical volume". Above the EW phase transition, all constituents move with velocity c (in any reference frame) and, thus, there will be no constituents which will be comoving (at rest) relative to the FLRW reference frame. If one would like to construct mathematical points (comoving with the reference frame) like the above mentioned center of mass (or, in special relativity, center of energy) out of the massless, ultrarelativistic gas particles, this procedure presumably requires that a length scale be available in order to e.g. specify how far the particles are apart (which is needed as input in the mathematical expression for the "center of energy").

[30]Apart from the necessity of physically based scales in order to set up the Weyl and cosmological principle, we may also recall (while insisting that we are not defending operationalism!) that it, of course, requires actual rods and clocks to establish these principles empirically – for instance it requires clocks to study the redshifts (cf. section 4.1) of galaxies moving away from us and it requires rods to probe the homogeneity of the matter distribution.

referring to (entangled) quantum constituents. What is a 'world line' or a 'particle trajectory' then?[31]

After these critical remarks on the (limited) physical foundation of the principles which underline the FLRW model, let us briefly review how the standard big bang solution is obtained. The most general line element which satisfies Weyl's postulate and the cosmological principle is the FLRW line element (see e.g. Narlikar 2002, p. 111 ff.):

$$ds^2 = c^2 dt^2 - R^2(t) \left\{ \frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right\} \tag{1}$$

where $R(t)$ is the scale factor, $k = 0, -1, +1$ correspond, respectively, to a flat, open and closed geometry, and r, θ, and ϕ are comoving (spherical) coordinates which remain fixed for any object moving with the expansion of the universe. The spatial part of the metric describes a curved space which is expanding with cosmological proper time t as described by the cosmic scale factor $R(t)$.

The symmetry constraints encoded in the FLRW metric require that the energy-momentum tensor of the universe necessarily takes the form of a perfect fluid. The fundamental equations which determine the dynamics of the FLRW metric are the Einstein equations, an energy-conservation equation and the equation of state (for the perfect fluid). Applying the Einstein field equations to the FLRW metric results in two equations (the Friedmann equations) which relate the energy and pressure densities to the Hubble parameter ($H \equiv \dot{R}/R$, where the dot denotes a derivative with respect to cosmic time t), see e.g. MTW p. 729. With perfect fluid matter, pressure and energy densities are proportional, $p = p(\rho) = w\rho$ (the equation of state), where e.g. $w = 0$ for dust (pressureless matter) and $w = 1/3$ for a radiation gas. The evolution of the scale factor $R = R(t)$ can be found by solving the Friedmann equations. A particularly simple solution is obtained in the flat, $k = 0$, case assuming w to be constant (see e.g. Coles and Lucchin 1995, p. 34):

$$R(t) = R_0 \left(\frac{t}{t_0} \right)^{2/(3(1+w))} \tag{2}$$

where R_0 and t_0 are, respectively, the present value of the scale factor and the present age of the universe. This (and other) solution(s) to the Friedmann equations illustrates (within classical GR) the idea of a big bang universe expanding from a singularity $R = 0$ at $t = 0$.

As already indicated, the standard physical interpretation of the t coordinate in the FLRW model is to identify it with the proper time of a *standard clock* at rest in the comoving system, i.e. $(r, \theta, \phi) = $ constant. In our view, a standard clock

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[31]The problem of setting up a cosmic time when quantum theory is taken into account is addressed in Rugh and Zinkernagel (2008). One may also ask whether individual quantum constituents, like a proton, are sufficient to function as rods needed to set up the spatial part of the reference frame with well-defined x-,y- and z- directions (even when quantum constituents introduce a physical scale, such as the proton radius, it may be questioned whether these constituents can point in a well-defined direction).

(or a core of a standard clock) in cosmology is any actual or possible scale-setting physical process which takes place in the cosmic epoch in question. The following two sections will address what these clock processes could be.

4   Possible types of clocks in cosmology

Below we will sketch some possible early universe clocks (giving standards of time). First we discuss the possibility of founding the time concept on the general features of the FLRW model (R, ρ, T). Then we look at some major candidates among the microscopic constituents of the early universe which might, more independently of the FLRW model, provide a physical basis for cosmic time.

In general, when we try to associate the parameter t $(= t(\mathcal{C}))$ with some physical process or a physical concept $\mathcal{C}$, we cannot require that the concept $\mathcal{C}$ does not depend on t. Indeed, insofar as time is a fundamental concept (cf. section 2), there are (virtuous) circles of this kind in any attempt to specify the time concept. However, we shall require that $\mathcal{C}$ is not just a mathematical concept, but a concept which has a foundation in physical phenomena (in which case we shall say that $\mathcal{C}$ has a physical basis). In particular, in order for $\mathcal{C}$ to provide a physical basis for time in a given cosmological epoch, these physical phenomena should refer to scales based on physics which are available at the epoch in question. Otherwise, if the required scales are more fine-grained than those available, the physical foundation of $\mathcal{C}$ will be insufficient. This may be remedied by introducing speculative physics with the required fine-grained scales, but in this case $\mathcal{C}$, and the time concept t $(= t(\mathcal{C}))$ in the given 'epoch', become as speculative as the physics employed.

Before looking at possible early universe clocks, we shall briefly illustrate the idea of founding the time concept upon physics involving well-known phenomena and scales. An elementary clock system involves the propagation of a light signal as well as a physical length scale. Such a clock was also discussed by Einstein (1949, p. 55):

> The presupposition of the existence (in principle) of (ideal, viz., perfect) measuring rods and clocks is not independent of each other; since a light signal, which is reflected back and forth between the ends of a rigid rod, constitutes an ideal clock,...

One way to provide a physical basis for the length scale involved in an Einstein clock is to refer to a spatially extended object of the same size within well-known physics. By contrast, if the length scale involved in the Einstein clock is smaller than physically based length scales from known physics, this clock – and the time concept based on it – will be speculative.[32] Compare this with Feynman's (Feynman et al 1963, p. 5-3) discussion of short times in particle physics where he comments on the

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[32]As mentioned above, if shorter time intervals (shorter length scales) are needed to provide a physical basis for the time of a cosmological epoch, one may introduce speculative elements into physics. As we shall see in section 5, such speculative physics is needed not just because the physical length scales within known physics may become 'too coarse' to found the time concept

by-then recently discovered strange resonances whose lifetime is inferred indirectly from experiments to be $\sim 10^{-24}$ seconds (see also subsection 4.4 below). To illustrate this time scale, Feynman appeals to what seems to be an intuitive physical picture since it (roughly) corresponds to "...the time it would take light (which moves at the fastest known speed) to cross the nucleus of hydrogen (the smallest known object)". Feynman continues

> What about still smaller times? Does "time" exist on a still smaller scale? Does it make any sense to speak of smaller times if we cannot measure - or perhaps even think sensibly about - something which happens in shorter time? Perhaps not.

Whereas the lifetime of strange resonances – or the Z^0 particle (section 4.4) – is rooted in physical phenomena (even if extracted from an elaborate network of theory dependent interpretations) we shall briefly look at Feynman's intuitive and illustrative picture of a light signal crossing a proton, and question whether this is a physical process which can function as a core of a clock (i.e. a physical process with a well-defined duration which can provide a physical basis for the corresponding time interval). The spatial extension of a proton is a physically motivated length scale, but its quoted value coincides with the proton's Compton wavelength (see also section 5.2). If the proton is to function as a "measuring rod" and the light pulse is to propagate from one end of the proton to the other then the light pulse needs to have wavelength components which are smaller than the extension of the proton. But the light pulse will then have sufficient energy to create proton-antiproton pairs and we will therefore have pair production of "measuring rods" (so does the light pulse reach the other end?). Moreover, elementary processes in quantum electrodynamics do not have well-defined space-time locations so a precise duration of a photon travelling a given distance cannot be specified (see e.g. Bohr and Rosenfeld (1933) and Stueckelberg (1951)). Thus, a closer inspection into the physical 'light-crossing-proton' process reveals intricate quantum field theory phenomena which questions whether this process is capable of providing a physical basis for the time scale of 10^{-24} seconds.

It should be emphasized that even if 10^{-24} seconds could be taken to correspond to a physical process (e.g. a light signal crossing a proton), this subdivision of the second cannot be achieved in the very early universe ('before' there are protons), and therefore this physical process cannot provide a physical basis for 10^{-24} seconds 'after' the big bang. Indeed, one should distinguish between how far the second can be subdivided at present (in terms of physical structure available now) and how far back in t the FLRW model can be extrapolated while maintaining a physical basis for time (and temperature).[33]

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in cosmology. Even worse, known physics suggests that *any* physical length scale – fine-grained or coarse – may disappear at some point in the very early universe.

[33]In fact, the electroweak processes (which at present may provide a physical basis for time scales of $10^{-24} - 10^{-25}$ seconds) take place at a cosmic time (according to the standard FLRW model) $\gtrsim 10^{-11}$ seconds after the big bang.

4.1 The cosmic scale factor R as a clock

An important large scale feature of the cosmological standard model is that the scale factor $R(t)$ is one-to-one related to the parameter t. Thus if we could devise a clear physical basis for the scale factor R, we could invert the mathematical formula $R = R(t)$ to give the parameter $t = t(R)$ as a function of R, and in this way base a concept of time on the scale factor of the cosmological model (see also MTW 1973, p. 730). For the flat $k = 0$ case, it is particularly simple to integrate the Einstein equations with perfect fluid matter $p = w\rho$, and we get (cf. equation 2)

$$t = t_0 \left(\frac{R}{R_0} \right)^{3(1+w)/2} \tag{3}$$

where, for instance, the exponent is equal to 2 ($w = 1/3$) for a radiation dominated universe.[34] For the scale factor to serve as a clock, however, one needs to have some bound system or a fixed physical length scale which does not expand (or which expands differently than the universe). Otherwise, we are simply replacing one mathematical quantity (t), with another ($R(t)$), without providing any physical content to these quantities. Indeed, if everything (all constituents) within the universe expands at exactly the same rate as the overall scale factor, then 'expansion' is a physically empty concept.[35] We can therefore ask:[36]

> **Observation #1:** If there are no bound systems – and not least if there are no other physically founded fixed length scales (cf. section 5.2-5.4) – in a contemplated earlier epoch of the universe, is it then meaningful to say that the universe expands? Relative to which length scale is the expansion of the universe to be meaningfully addressed?

Implementing a scale via boundary conditions.
It is customary to put in a time scale and a relative length scale for the scale factor as a starting (boundary) condition of the cosmological model. For example we could employ as an input in the FLRW model that the present age of the universe is $t \sim 14$ billion years ($t \sim 4 \times 10^{17}$ seconds) and set the present relative scale factor (R/R_0) to unity (see e.g. Narlikar 2002, p. 136, or Kolb and Turner 1990, p. 73). By relying on present physical input scales, it thus seems that the scale factor in equation (3) can serve as a clock as far back in cosmic time as desired. This possibility, however, will depend on whether the (relative) scale factor has a physical basis during the backward extrapolation (cf. section 2 and below).

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[34]The precise functional relationship between t and $R(t)$ depends on which particles exist at the relevant temperature, and of their interaction properties, see e.g. Narlikar (2002, p. 171) or Kolb and Turner (1990, p. 65, Fig. 3.5).

[35]Eddington, for example, emphasized the importance of the expansion of the universe to be defined relative to some bound systems by turning things upside-down: 'The theory of the "expanding universe" might also be called the theory of the "shrinking atom" (Eddington 1933, quoted from Whitrow 1980, p. 293). See also Cooperstock et al. (1998).

[36]In this and the following section, we shall attempt to clarify the discussion by emphasizing key observations in some of the subsections.

The physical basis of the relative scale factor can for instance be given in terms of red shifts ($1+z = R_0/R$). In turn the physical meaning of (redshifted) light depends on the physical meaning of frequency and wavelength, and, as discussed in section 4.3, this requires the existence of relevant physical length scales (as observation 1 indicates).[37]

4.2 Temperature as a clock

The relation between the FLRW t parameter and the occurrence of the various (more or less sharply defined) epochs, in which different layers of physics (atomic, nuclear,...) come into play, is identified via a time-temperature relation. In order to establish this relationship between time and temperature one first needs to relate the energy density to temperature. According to the black-body radiation formula (Stefan-Boltzmann law) the energy density (ρ) of radiation, which is the dominant energy contribution in the early universe, is connected to the temperature T as

$$\rho = aT^4 \equiv \frac{8\pi^5 k^4}{15h^3 c^3}\, T^4 \tag{4}$$

which gives an energy density $\rho \approx 4.4 \times 10^{-31} kg/m^3$ of the present $T \sim 2.7$ K microwave background (comprised of a nearly uniform radiation of photons), see e.g. Weinberg (1972, p. 509 and 528).[38] Moreover, throughout most of the early history of the universe the temperature T is simply inversely proportional to the scale factor: $T \propto 1/R = 1/R(t)$.[39] Thus, by using the relation $t = t(R)$ (equation 3) – obtained by integrating the Einstein equations for the radiation dominated FLRW universe – one may arrive at a relationship between t and T.

The more exact relation between time and temperature depends however crucially on the temperature range considered, since different particles and different

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[37]Similar remarks apply to the option of using the density ρ (rather than the cosmic scale factor R) as a clock. In a radiation dominated universe (cf. Weinberg 1972, p. 538) we have $t \sim (G\rho)^{-1/2}$. As in the case of the scale factor, however, we need to have physical scales (for volume and energy) in order for the energy density concept ρ to function as a clock in a given cosmological epoch. Without a fixed volume concept (that is a scale for length, e.g. a non-expanding bound system), there is no physical basis of an energy density (which changes with time). Furthermore, the fixed scales need to be based on known physics if the density clock is to be non-speculative.

[38]To obtain the total (dominant) energy density in the early universe one has to sum over all the (spin/polarization states of the) species of relativistic particles (photons, neutrinos, ...), see e.g. Narlikar (2002, p. 170-171). Thus equation (4) will be multiplied by a factor g_* equal to the number of effective relativistic (those species with mass $m_i c^2 \ll kT$) degrees of freedom, for example $g_* = 2$ (2 polarizations) for a photon. The number g_* increases considerably with temperature. At $T \gtrsim 300$ GeV $\approx 10^{15}$ K all the species in the standard model of particle physics (8 gluons, $W^\pm$, Z^0, 3 generations of quarks and leptons, and the Higgs) are effective relativistic degrees of freedom, and $g_* > 100$ (see also Kolb and Turner 1990, p. 64-65).

[39]Such a relationship $T \propto 1/R(t)$ can be understood intuitively if we assume that a typical wavelength of the black body-radiation is stretched as the universe expands and simply scales as $\lambda \propto R(t)$ (i.e. proportional to the scale factor). However, the input assumptions really involve the application of standard equilibrium thermodynamics (thermal equilibrium is assumed), some simplifying approximations, and the application of principles such as covariant energy conservation and the constancy of the entropy in a volume $R(t)^3$. See e.g. Weinberg (1972), Sec. 15.6.

particle properties come into play at different temperatures. Analytic solutions can often not be obtained and one has to resort to a numerical calculation to 'integrate' through eras in which complicated physical processes take place, for example the era corresponding to temperatures around $T \sim 6 \times 10^9$ K in which the process of annihilation of e^-e^+ pairs takes place. (The electron mass m_e corresponds to a temperature of $T \sim m_e c^2/k \sim 6 \times 10^9$ K). This is a process in which the ratio m_e/kT of the electron mass to the temperature plays a decisive role and a complicated formula governs how to arrive at the relationship between time t and the temperature T,

$$ t = - \int \left(\frac{8}{3} \pi G a T^4 \mathcal{E}(\frac{m_e}{kT}) \right)^{-1/2} \left(\frac{dT}{T} + \frac{d\mathcal{S}(m_e/kT)}{3\mathcal{S}(m_e/kT)} \right) \tag{5} $$

where $\mathcal{E}(x)$ and $\mathcal{S}(x)$ are two quite involved mathematical functions of the argument $x = m_e/kT$ (Weinberg 1972, p. 537-540).

When the temperature of the universe is well above the e^-e^+ annihilation temperature $T \sim 6 \times 10^9$ K (but below the quark-hadron phase transition, as well as the $\mu^-\mu^+$ annihilation temperature of $\sim 1.2 \times 10^{12}$ K), the relationship between time t and temperature T simplifies considerably (Weinberg 1972, p. 538):[40]

$$ t = \left(\frac{c^2}{48\pi G a T^4} \right)^{1/2} \sim 1 \text{ second} \times \left(\frac{T}{10^{10} \ K} \right)^{-2} \tag{6} $$

According to this equation, starting at $T = 10^{12}$ K, it took roughly $\sim 10^{-2}$ seconds for the temperature to relax to 10^{11} K, and roughly ~ 1 second for the temperature to drop to 10^{10} K. To establish time-temperature relations similar to equation (6), as the temperature T increases and the FLRW model is extrapolated further backwards, requires knowledge of the particle species in existence and of their properties.

The physical basis for temperature
In order to employ temperature as a clock one needs to provide an account of the physical basis for the concept T which appears in relations such as (6). The concept of temperature is roughly a measure of the average energy of the particles (the available energy per degree of freedom). In a non-relativistic limit this energy is in turn connected to the velocity of the particles, $kT \propto \langle 1/2mv^2 \rangle$. Thus, in order for the temperature concept to have physical meaning one needs a well-defined mass, time, and length scale. For ultra relativistic particles (like massless photons) which move with the velocity of light, c, the temperature concept is related to the average energy density which demands a well-defined energy and volume scale. We can thus state:

> **Observation #2**: The temperature concept is intimately connected to length and energy (or mass) scales. Therefore one cannot have a physical basis of the temperature concept when such scales are not available.

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[40]Similar relations with different prefactors also hold in other intervals of temperature where the effective number of relativistic degrees of freedom remains constant, cf. Kolb and Turner (1990, p. 64-65); Narlikar (2002, p. 170-171).

Moreover, if the available scales are not of relevant size (not sufficiently fine-grained), the temperature concept will be insufficiently founded. If scales of the relevant size are provided by speculative physics, the temperature concept will be speculative as well.

We should also recall that temperature is a statistical concept which has no meaning for individual particles but only for ensembles: There must be a concept of (nearly) local thermodynamic equilibrium in order to speak about a temperature, see also Kolb and Turner (1990, p. 70 ff.). The standard definition of temperature in thermodynamical equilibrium reads

$$1/T = (\partial S/\partial E)_V \tag{7}$$

where S is the entropy and E the free energy, and the volume V is kept fixed. It is again clear from this definition that a length scale (volume scale) and an energy scale are presupposed (in sections 5.3 and 5.4, we will question this presupposition in the 'desert epoch' above the Higgs phase transition at $T \approx 300$ GeV $\sim 10^{15}$ K).

4.3   The black body radiation clock

In connection with the possibility of a temperature clock, we shall now examine if one can use the frequency of the radiation (the massless constituents) of the universe to provide a physical basis for the concept of temperature or, directly, the concept of time. In thermodynamical equilibrium at a temperature T there is a distribution of the photons among the various quantum states with definite values of the oscillation frequencies ω as given by the Planck distribution (black body radiation). The average oscillatory frequency grows proportionally to the temperature $\hbar\omega = kT$ (where k is the Boltzmann constant translating a temperature into an energy scale).

Could we envisage taking a large ensemble of photons[41] in the early universe and extract the average wavelength or oscillation frequency of the ensemble?[42] One could then imagine converting the average frequency ν into a time scale $t \sim 1/\nu$, and in this way establishing a physical time scale at the temperature T. This would be a promising proposal for a 'pendulum' (oscillation frequencies of massless particles) which abounds in the universe and which could possibly even function down to Planck scales, thus providing a physical basis to the concept of time (or temperature) right down to Planck scales.

However, just like in the above examples, this frequency clock relies on physically based input scales (in order for ν to have a physical basis). One may attempt to use the radiation field to establish a time scale directly, without referring to an external length scale, by counting the number of oscillations of a test charge which

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[41]Or any particle species whose mass is much smaller than kT so that it can be considered effectively massless and treated on the same footing as photons.

[42]Since frequency depends on the chosen reference frame, we might imagine some fictitious rest frame, say, in which the the momenta $\hbar\boldsymbol{k}$ of all the photons sum up to zero.

is located in the electromagnetic radiation field. But how many oscillations should we count in order to put a mark that we now have 1 second (or 10^{-40} seconds)? If the oscillation frequency is not linked to some physical process setting a scale it appears downright impossible to convert a number of oscillations into a time standard (given in any fixed time unit).[43] One would need, for example, photons with a well-defined frequency produced, say, in an annihilation process of particles with a given rest mass or simply refer to a specified temperature scale, since the oscillation frequency (by the black-body radiation formula) is linked to temperature. Such a procedure would take us back into the discussion of the above subsection 4.2.[44]

The fact that electromagnetic light is not able, by itself, to set a length scale can also be expressed by the observation (section 5.3) that the massless standard model (which includes the electromagnetic interaction) is scale invariant.

4.4   Decay of unstable particles as clocks

We proceed in this subsection to give a short discussion of whether the decay processes of some material constituents in the universe could provide clocks.

If we have N_0 identical particles and we suppose for a moment that we can trace and follow the behavior of each of these, then we can imagine counting the number of remaining $N(= N(t))$ particles after some time t. In quantum theory the decay of an individual particle is described by probabilistic laws so we need a statistical averaging procedure to obtain a well-defined decay time (life time) τ. From the number N of remaining particles one may then estimate the time t passed as

$$t = \tau \ \times \ \log(N_0/N) \tag{8}$$

In this sense, the number N of remaining particles functions as a (statistical) clock. Given that we are interested in processes which might function as clocks in the very early universe, it would be most relevant to find decay processes which proceed very fast. For example, we could imagine considering e.g. the decay of the muons $\mu^- \to e^- \bar{\nu}_e \nu_\mu$, or of the Z^0 particles, $Z^0 \to f\bar{f}$, which can decay into any pair of fermions.[45]

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[43]Similar remarks apply, of course, to the physical significance of the wavelength $\lambda = c \times 1/\nu$ of the electromagnetic wave. Such a wavelength is lacking any physical basis if there is no length scale setting process to which it can be related.

[44]The situation can be illustrated by an analogy. The frequency for small oscillations of a pendulum of length ℓ in a homogeneous gravitational field is given by $\omega = 2\pi/T = \sqrt{g/\ell}$. It is, however, impossible to relate a counted number of oscillations of this pendulum to, say, the scale of a second unless we know the value of g/ℓ. In general, we need (extra) input physics in order to relate a counted number of oscillations to any fixed time unit.

[45]The fastest process, within experimental particle physics, is the estimated decay time, $\sim 10^{-25}$ seconds, for the decay of a massive Z^0 particle with mass $M_Z \sim 91.1876 \pm 0.0021 \ GeV/c^2$ (the Z^0 is one of the three massive mediators of the weak interactions). Note that such a tiny interval of time has not been directly observed, but is inferred indirectly from resonance widths and the Heisenberg uncertainty relation: The quoted lifetime can be estimated (as $\sim \hbar/\Gamma$) from the measured resonance width $\Gamma = 2.4952 \pm 0.0023$ GeV (see the "Gauge & Higgs Boson Summary Table", p. 31 in S. Eidelman et al. (2004)).

Two problems should be kept in mind (and further examined) if one would like to use such (actual or counterfactual) decay processes as a physical basis for time or the time scale in the early universe: (1) Decay processes are quantum mechanical and therefore statistical in nature. There is thus a minute probability that the number of particles will remain constant for a 't interval' (or even grow if particles are created, say, by the opposite process $e^-\bar{\nu}_e\nu_\mu \to \mu^-$). One has to check whether this means that a time concept based on the decay of particles could stop or even go backwards in these two cases (cf. Rugh and Zinkernagel 2008). (2) As mentioned above, the statistical nature of the decay clock also means that we need an averaging procedure to obtain a well-defined time scale. But in which reference frame is this averaging procedure (in principle) to take place? The expected decay time for an individual particle equals the lifetime τ *only in the rest frame* of the decaying particle. With respect to the comoving reference frame (in which cosmic time is defined and in need of a physical basis, cf. section 3.2) the expected decay time for each particle will be multiplied by the Lorentz factor γ which depend on the velocity of the decaying particle. This velocity in turn depends on the temperature T. Thus, the decay time relative to the comoving reference frame grows (linearly) with temperature T, and an independent physical basis for temperature is required in order for the decay clock to fix a well-defined scale. In any case, all known decay clocks appear to be doomed to fail above the electroweak phase transition since at this point the μ^-, Z^0, and the entire spectrum of massive particles, become massless (see section 5.3).

Even if there are no decays, there may still be *interactions* among the massless (charged) constituents of the ultrarelativistic plasma which is envisaged to exist above the electroweak (Higgs) phase transition. Since the physics is invariant under scale transformations (section 5.4) such processes will, however, not by themselves be able to set a fixed scale for time and length (at most, it may be possible for such processes to provide order clocks). One may, for instance, imagine introducing a 'statistical clock' based on the interaction rate Γ of the particles in the relativistic plasma.[46] If we are following a particle, and each time it interacts we count it as a 'tick', we will have a statistical clock in which the length of the ticks will fluctuate around some mean value ($\tau = 1/\Gamma$), and the mean free path ($\ell = c\tau$) sets a length scale (a definition which, for example, does not rely on the notion of a bound system).[47] The interaction rate can be estimated in the early universe to be $\Gamma \sim \alpha kT/\hbar$, where α is the relevant coupling constant, e.g. $1/137$ for electromagnetism, and T is the temperature. In fact since $\tau = 1/\Gamma \sim 1/T$ the (interaction rate) clock ticks slower and slower as the universe expands. We note that the time and length

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[46]This clock was suggested to us by Tomislav Prokopec.

[47]Note that this clock needs a clear and unambiguous definition of the concept of 'interaction of two (massless) particles'. Otherwise how do we decide when two particles interact? Is it when two point particles coincide in the same space-time point (this involves renormalization problems, and a prescription of how to identify 'the same space-time point' which do not involve rods)? Is it when the particle becomes 'asymptotically free' after a collision, cf. the S-matrix formalism (then when do we count)?, Or is it when the particle is x meters away from the collision partner (then we need rods, or a length scale again)? The problem is probably not eased if one takes into account the quantum nature of the particles (entanglement).

($\ell = c\tau$, the mean free path) set by this clock scales exactly as the cosmological scale factor $R \propto 1/T$. This entails (1) that the clock is not able to set a fixed length scale relative to which the expansion of the universe (expansion of the scale factor R) can be meaningfully addressed; and (2) that the clock requires a physical foundation for temperature T if the tick-rate is to be employed as a clock which can provide a physical basis for cosmic time scales given in some fixed unit of time (e.g. a second).[48]

4.5   Atomic (and nuclear) clocks

In the realm of atomic and nuclear physics there are many physical systems which have characteristic and well-defined oscillations and periodicity. A photon produced by a transition between two well-defined quantum states with energies E_1 and E_2 yields a well-defined frequency establishing a characteristic time scale $\omega^{-1} = \hbar/(E_1 - E_2)$.[49] If we consider the simplest bound system in atomic physics, the hydrogen atom, it has a spatial extension of $\sim 10^{-10}$ m (the Bohr radius) whereas it emits light with wavelengths of many hundred nanometers. Thus, the time scale of the transitions (between quantum states) in a bound system like the hydrogen atom is much longer (i.e. more 'coarse') than the time scale it would take light to cross the spatial extension of the system. The latter would correspond to the "Einstein light clock", mentioned in the introductory remarks of section 4, for the case of light traversing the spatially extended system of a hydrogen atom.

The spectral lines of hydrogen, the simplest bound atomic system, were explained by Niels Bohr in 1913, and since then a wide range of quantum mechanical transitions have been identified within atomic and nuclear physics. The unit of a second is presently defined by referring to a physical system within atomic physics: One second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between two well-defined hyperfine levels of the ground state of the cesium-133 atom.[50]

Even if there were atomic systems before the 'atomic age' of the universe (from $\sim 10^{13}$ seconds after the big bang – the time of the emission of the cosmic microwave background radiation – and onwards), it is clear that there are no atoms before nucleosynthesis (and also clear that there could not, counterfactually, have been any – given the physical circumstances). Indeed, any atomic clock will melt at a

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[48]More generally, in order to know that the basic tick rate is changing we need some physical quantity that breaks the (conformal) scaling symmetry.

[49]One should not think of these frequencies as being totally sharply defined, as there is always a line width (i.e. an uncertainty $\triangle\omega$).

[50]In any atomic clock, such as the cesium-133 clock, one needs two components. (1) A frequency calibration device: The frequency of a classical electromagnetic radiation signal is calibrated to maximize the probability of a certain hyperfine transition in a cesium atom. The procedure involves a large ensemble of cesium atoms and the precision is limited by the statistics. (2) A counter: There has to be a mechanism which can count 9 192 631 770 periods of the radiation and thus (irreversibly) mark '1 second' when such a number has been counted. See e.g. C. Hackman et al. (1995) or C. Audoin et al. (2001).

certain temperature and the use of atomic systems as a physical basis for the time concept beyond this melting temperature is thus excluded.

5   The parameter t in cosmic 'history'

In this section we shall attempt more explicitly to examine the t concept, and the possibility to identify the 'core' of (comoving) clocks, within the various contemplated epochs of cosmic history. A key parameter which determines the characteristic physics in each epoch is the temperature T since it is the transition temperatures of various phase transitions (in the realm of nuclear and particle physics) which give rise to the quoted times t of each cosmic epoch.[51] We emphasize again that when we refer to a time 'after the big bang' (after the BB) in the following subsections, we are (for lack of viable alternatives) following the standard convention by which t is 'counted forward' from a fictive mathematical point (the singularity in the FLRW model).

5.1   Nucleosynthesis $\sim 10^{-2} - 10^2$ seconds after the big bang

Since their inception in the late 1940's, primordial nucleosynthesis models have yielded predictions of the relative abundances (measured relative to the abundance of hydrogen) of various light nuclei. These estimates are based on a detailed understanding of the possible nuclear reactions among light nuclei which can take place at different temperatures.[52]

According to the standard cosmological model, the synthesis of the light nuclei is established over a time span of some minutes. The span of cosmic time from $t \sim 10^{-2}$ to 10^2 seconds after the BB is estimated (via the FLRW solution) from the interval of cosmic temperatures (from $\sim 10^{11} K \sim 10$ MeV to $\sim 10^9 K \sim 0.1$ MeV) at which the various primordial nucleosynthesis processes take place. The cosmic time span available to the various nuclear reaction processes is crucial for this scenario to produce the observed abundances of light nuclei.[53] Thus, in the era of cosmological nucleosynthesis there is some (even observational) handle on the conception of cosmic time, and there are time-scale setting nuclear processes on which we may base (cores of) clocks in this era. The nucleosynthesis era therefore provides an example in which cosmic time scales in early universe cosmology are correlated with important time scales in rather well understood micro-physical processes (within the realm of nuclear physics).

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[51] A quick summary of the contemplated epochs (eras) in cosmology may be found e.g. in Coles (2001, p.348). Cf. also e.g. Weinberg (1972, Sec. 15.6) and Narlikar (2002, Chapt. 6.).

[52] Agreement with astronomical observations is obtained by fitting the baryon to photon ratio η within the range $\eta = n_B/n_\gamma \sim (4 \pm 2) \times 10^{-10}$, see, e.g. Schramm and Turner (1998).

[53] For example, the time span of the processes relative to the neutron lifetime is crucial for the production of helium. The free neutron decays in the weak decay $n \to p^+ + e^- + \bar{\nu}$ and has a lifetime $\tau_n \sim 15$ minutes. If the neutron lifetime were much shorter, the neutrons would have decayed (within the available cosmic time of $\sim 10^2$ seconds) before deuterium could form (and the helium production would never get started).

5.2 The quark-hadron phase transition: $\sim 10^{-5}$ seconds

Before the time of nucleosynthesis, the universe is believed to have been in the lepton era in which the dominant contribution to the energy density comes from electrons, electron-neutrinos, and other leptons (positrons, muons, etc.). Even earlier, the universe is envisioned to have entered the hadron era in which the material content is mainly comprised of hadrons, such as pions, neutrons, and protons.

A main focus of our discussion is the – in principle – availability of (sufficiently fine-grained) length and time scale setting physical objects or processes (cores of rods and clocks) at the given cosmic moment in question. For this discussion a most important event takes place at a transition temperature of $T \sim 10^{12}$ K ($\sim 10^{-5}$ seconds after the big bang). At this point, one imagines (as we extrapolate backwards toward higher temperatures) that the hadrons dissolve, their 'boundaries' melt away, and the quarks break free. So the universe is comprised of structureless particles – quarks, leptons, gluons, photons – in thermal equilibrium. Above this so-called quark-hadron transition one imagines the creation of 'the quark-gluon plasma', a hot and dense mixture of quarks and gluons, see e.g. Peacock (1999, p. 305).[54]

Above the quark-hadron phase transition there are no bound systems left. Below we shall discuss various physical properties of the microscopic structure of matter which, apart from bound systems, may set a physical length scale. As we shall see, it is not clear if such length scales as the Compton wavelength (associated with a massive particle) and the de Broglie wavelength (associated with the momentum of the particle) constitute physical length scales which, e.g. together with a light signal, can function as the core of a clock (a physical process with a well-defined duration). Thus it may not be unreasonable to consider the following possibility:

> **Observation # 3:** If a bound system is a minimal requirement in order to have a physical length scale (which can function in the core of a clock), then it becomes difficult to find a physical basis for the time scale above the quark-gluon transition at $t \sim 10^{-5}$ seconds.

The idea of liberation of quarks in the quark-hadron phase transition is widely accepted but there is no consensus as concerns the details of this transition and the physical structure of the quark-gluon plasma; see, for example, reviews by McLerran (2003) and Müller and Srivastava (2004). In particular, there is no consensus as concerns the physical structure of the quark-gluon plasma phase. The transition temperature for the quark-hadron phase transition is set by the Λ_{QCD} parameter which sets a scale of energy in the theory of strong interactions (the only dimensional

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[54]Before the establishment of the quark model in the 1970's, cosmologists were reluctant to even speculate about times earlier than 10^{-5} seconds, cf. e.g. Kolb and Turner (1990, p. xiv): "...it was believed that the fundamental particles were leptons and hadrons, and that at a time of about 10^{-5} sec and a temperature of a few hundred MeV the strongly interacting particles should have been so dense that average particle separations would have been less than typical particle sizes, making an extrapolation to earlier times nonsensical".

quantity in QCD); see e.g. Weinberg (1996, Vol. II, p. 153-156). The phase transition temperature is roughly $T = T_c \sim \Lambda_{QCD} \sim 0.2$ GeV $\sim 10^{12}$ K.[55]

The Compton and the de Broglie wavelength as possible physical length scales above the quark-hadron transition

Bound systems, like atoms, set a (coarse) time scale through transitions between energy levels, and a (finer, but more theory dependent) length scale through their spatial extension. But are bound systems really needed in order to have a rod (a length scale) which could function e.g. in an Einstein light-clock (mentioned in the beginning of section 4)? As other possibly relevant length scales, physicists may point to the Compton and the de Broglie wavelength of the elementary particles. Although these are physically motivated length scales which are independent of the existence of bound systems, we question whether these can function in the core of a clock (providing physical processes with well-defined duration) in the very early universe.

Consider first the Compton wavelength. In and above the quark-gluon phase, the quarks and leptons still possess the physical property of mass. Thus, one may still have length scales if the Compton wavelength $\lambda = \lambda_C = \hbar/(mc)$ of these particles can be taken to set such a scale.[56] As discussed in the beginning of section 4, however, the quantum field theoretical phenomenon of pair production and the difficulties of precisely locating QED processes in space and time make it difficult to maintain that the Compton wavelength divided by c corresponds to a physical process which can function as the core of a clock.[57]

Apart from the Compton wavelength, a particle in quantum theory is associated with a de Broglie wavelength $\lambda_{dB} = h/p$, where h is Planck's constant and p is the momentum of the particle (or wave). Indeed, the de Broglie wavelength is a

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[55]The precise prefactor has to be evaluated by numerical calculations (it is not far from ~ 1) and it differs slightly for the two phase transitions (chiral symmetry breaking and deconfinement) which are investigated, e.g. in lattice simulations, in connection with the formation of the quark-gluon plasma (see Laermann and Philipsen (2003)).

[56]Note, that the Compton wavelength is not related to the physical extension of the particle in question. For instance, the electron (which has no known spatial extension) has a larger Compton wavelength (since it has a smaller mass) than the proton which has spatial extension of about 1 fermi = 10^{-15} meter. The Compton wavelength rather sets a distance scale at which quantum field theory becomes important since at those wavelengths there is enough energy to create a new particle, $\hbar\omega_C = \hbar c/\lambda_C = mc^2$. Thus, the Compton wavelength is the length scale at which 'pair production' of particle-antiparticle pairs occurs. (We should also note that a force, e.g. the weak force, mediated by a massive particle is effectively described by the Yukawa potential $V(r) \sim 1/r \exp(-r/\lambda_C)$ which has a characteristic range set by the Compton wavelength of the massive particle).

[57]Even if we grant that the Compton wavelength is a length-scale setting physical process (that is, the length scale at which pair production occurs) we note that since $\lambda = \lambda_C = \hbar/(mc)$ is a scalar it will – considered as (some sort of) a core of a 'measuring stick – not be able to point in any direction in 3-space (even in principle). Thus it will hardly provide a physical foundation for the concept of 'pointing in a direction' which appears to be necessary to give a physical underpinning of the concept of 'isotropy' (an input assumption in building up the FLRW model in cosmology), see section 3.2.

physical length scale for example in a double slit experiment where the particle (e.g. an electron) interacts with itself (λ_{dB} can be inferred from the interference pattern). In our assessment, however, one can hardly use the de Broglie wavelength as the fundamental physical length scale (which could function e.g. in an Einstein clock) in the early universe. A first problem is that the definition of a de Broglie wavelength depends on there being a fixed reference frame (with respect to which the momentum can be specified), and part of our reason for asking for length scales (rods) is precisely that they are needed as a physical basis to set up the (comoving) coordinate frame. Setting up this coordinate frame (in order to avoid a vicious circularity) should therefore rest on other length scale setting processes besides the de Broglie wavelength. Moreover, in the (comoving) coordinate frame the material constituents (the particles) are at rest (in average). But in the rest frame the momentum of the particle is zero, $p = 0$, and the de Broglie wave length of the particle is thus infinite (undefined). This makes the de Broglie wavelength unsuitable as a fundamental physical length scale.[58]

Moreover, in the ultrarelativistic limit, the rest mass of the particle is negligible in comparison with the kinetic energy (so $E \approx E_{\text{kin}} \approx pc$), and the particle behaves effectively as a photon (that is, it is effectively massless).[59] Thus, in the ultrarelativistic limit, the de Broglie wavelength of a particle is analogous to the wavelength of a photon. As we discussed in section 4.3, such a wavelength (or the corresponding frequency) cannot by itself set a length scale, as electromagnetism is a scale invariant theory.

5.3 The electroweak phase transition: $\sim 10^{-11}$ seconds

The standard model of the electroweak and strong interactions is a gauge theory based on the general framework of quantum field theory (QFT). The model embodies, at present, a Higgs sector (comprising a (set of) postulated scalar field(s) ϕ) which makes it possible to give masses to various constituents of the standard model (invoking the idea of spontaneous symmetry breaking) without destroying renormalizability of the model. At low temperatures the quantum mechanical vacuum expectation value of the Higgs field is non-zero.[60] The electroweak phase transition occurs, it is believed, at a transition temperature of $T \sim 300$ GeV $\sim 10^{15}$ K when the universe was $\sim 10^{-11}$ seconds old. (Kolb and Turner 1990, p. 195). Above the phase transition the Higgs field expectation value vanishes,

$$< \phi > = 0. \tag{9}$$

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[58]The length of any rigid rod is frame dependent in special relativity. But a proper 'measuring rod' should have a well-defined length in the rest frame of the measuring rod (a well-defined 'rest length') and the rest de Broglie wavelength is infinite.

[59]The de Broglie wavelength is proportional to $1/p$. Since the momentum grows with temperature, it is a length scale which shrinks with temperature (note that this is not the case for the length scales set by bound systems and the Compton wavelength). Thus λ_{dB} does not give a fixed length scale relative to which an expanding cosmic scale factor, say, could be gauged.

[60]This is one of several sources in QFT of the so-called cosmological constant problem, see e.g. Rugh and Zinkernagel (2002).

This transition translates into *zero rest masses* of all the fundamental quarks and leptons (and massive force mediators) in the standard model.

Thus, even if Compton wavelengths (corresponding to the non-zero rest masses) could set a length scale below the electroweak phase transition point, above the transition there are no Compton wavelengths for the massless quarks, massless leptons and massless W's and Z^0. Also, the possibility to correlate the t-parameter with decay processes such as the decay of e.g. the Z^0 particle is not possible above the phase transition point since massless particles will not decay; see e.g. Fiore and Modanese (1996).

In spite of the zero mass of the quarks and the leptons, there might still be a rudiment of mass left in the model. Most of the mass of a composite bound system like the pion (and also protons, which have melted away at this temperature) does not arise from the u and d rest masses, but from the highly complicated gluonic self-interaction of the QCD colour fields. Most of the pion mass, taken to be ~ 0.6 GeV above the quark-hadron transition (D. Diakonov, personal communication), might thus survive the transition where the fundamental quarks become massless. However:

(1) It is questionable whether a pion survives as a bound system at temperatures, $T \gtrsim 300$ GeV, which are roughly ~ 500 times larger than its rest mass above the quark-hadron transition (and more than one thousand times the QCD scale $\Lambda_{QCD} \sim 0.2$ GeV).

(2) Even if a QCD bound system, like a pion, could survive as a bound system at these high energies, a pion mass of ~ 1 GeV is to be considered 'effectively massless' relative to temperatures $T \gtrsim 300$ GeV. If a particle of rest mass ~ 1 GeV has an energy (kinetic energy) of ~ 300 GeV it will move with a Lorentz γ-factor of $\gamma \approx 300$ (ultrarelativistic limit). Thus the situation resembles the problem – discussed in section 4.3 – of providing a physical foundation for the concept of temperature $T \sim 300$ GeV from a determination, in principle, of the frequency (or wavelength) of the photon. The wavelength of a photon sets a length scale only when reference can be made to microstructure (outside the theory of scale-invariant electromagnetism). More quantitatively, a photon wavelength of order $\sim \hbar c/(kT) \sim 10^{-18}$ meter (corresponding to temperatures ~ 300 GeV) should have its physical basis in length scales $\sim 10^{-18}$ meter defined by microstructure which is at rest relative to the comoving coordinate system.[61] The small non-zero rest mass ~ 1 GeV of a pion *does* break the scale invariance which is a symmetry property of a perfectly massless photon. But in our assessment the relevant length scale of this symmetry breaking (the Compton wave length of a ~ 1 GeV pion is ~ 0.2 fermi

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[61]In our assessment the length scales should be length scales ('measuring sticks') for physical structure which is at rest in the comoving cosmic coordinate system. (Recall that the cosmic standard clocks and measuring rods are at rest in the comoving coordinate system). Indeed, it seems unreasonable to ground the concept of a physical scale on the fact that a 'measuring stick' (at a given length scale) which moves with velocities arbitrarily close to c can get arbitrarily Lorentz contracted. If one were to allow Lorentz shortened objects as a basis for physical scales, then the meter stick in Paris would be a physical basis for the Planck scale if we consider it from a moving system with a γ-factor of 10^{43}!

$= 0.2 \times 10^{-15}$ meter) is insufficient to provide a physical basis for the energies and temperatures operating at scales of ~ 300 GeV. The pion 'measuring stick' is more than one hundred times too 'coarse'!

In closing this brief discussion of length scales which may or may not be established by the existence of a ~ 1 GeV rest mass particle, it is instructive to compare the time and energy scales which are associated with such a particle (of rest mass 1 GeV) and the time and temperature (energy) scales of the universe at the times of the electroweak phase transition. For the purpose of this comparison, we assume that the Compton wavelength of a massive particle is able to set a physical length scale (see also discussion in section 5.2): A rest mass of 1 GeV then corresponds to length scales (via the Compton wave length) of ~ 0.2 fermi $= 0.2 \times 10^{-15}$ meter, and time scales of $\sim \hbar/(mc^2) \sim 10^{-24}$ seconds. Thus, this time scale has a very fine resolution (is sufficiently fine-grained) relative to the 'age of the universe' ($\sim 10^{-11}$ seconds at the point of the electroweak phase transition). On the other hand the same rest mass of 1 GeV corresponds to energy and temperature scales of ~ 1 GeV $\sim 10^{13}$ K which (given the argumentation above) appear insufficient (by a factor of 300) to provide a physical basis of the physics (e.g. the temperature concept) operating at energy and temperature scales of ~ 300 GeV $\sim 3 \times 10^{15}$ K.

In the cosmological context, both time and temperature scales need to be based in sufficiently fine-grained physical structure in order to yield a physical basis for the time-temperature relation (such as equation (6)). (Recall that it is *temperature* which determines the time of the phase transition, and thus – not least – temperature which needs a physical basis).

5.4   Nearly scale invariance above the electroweak phase transition

We now mention a significant problem which arises when we enter a phase where the masses of the fundamental particles disappear. The question is whether we can point to *any* relevant physical phenomena which set a physical length scale (fine-grained or not) above the electroweak phase transition where the universe is envisaged to contain structureless constituents of massless fermions (leptons and quarks) and bosons (electroweak photons and strongly interacting gluons).[62]

The gauge theories of the standard model exhibit a symmetry (modulo some small effects that we shall address in a moment) which implies a scale invariance of the theories when the masses of the particles are zero.[63] The scale symmetry

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[62]Note that a universe of only massless constituents will be described in terms of pure radiation, and we are thus confronted with a situation similar to the one in section 4.3 concerning the blackbody radiation 'clock', but in this case without any available material length scales to physically interpret the frequency of the radiation.

[63]The symmetry (exhibited by a massless gauge theory) is known as conformal invariance. Conformal symmetry is a stronger symmetry than scale invariance: Scale invariance requires invariance under uniform length rescaling, whereas conformal invariance also permits a non-uniform local rescaling and only requires that angles are kept unchanged. (The difference between scale and conformal symmetry is roughly analogous to the difference between global and local gauge

operation, which is in conformity with special relativity (keeping c invariant) and quantum mechanics (keeping $\triangle \hat{x} \triangle \hat{p} \geq \hbar$ and $\triangle t \triangle \hat{E} \geq \hbar$ invariant), is the set of transformations (with scaling parameter λ),

$$t \to \lambda\, t \ , \ \ \vec{x} \to \lambda\, \vec{x} \ , \ \ E \to 1/\lambda\, E \ , \ \ \vec{p} \to 1/\lambda\, \vec{p} \tag{10}$$

The transformation of other physical quantities under this scaling operation follows from these transformation rules.[64]

The constants of the governing theory (the quantum field theory of gauge interactions) such as $\hbar$ and c are held invariant under the transformations (10). Constants like the electromagnetic fine structure constant $\alpha_e = e^2/(\hbar c)$ are also invariant under the transformations. If masses were present they would have to be held constant (otherwise we would change the theory in question), but the equations of the theory would then not be invariant under the scale symmetry operations (10). In this way the presence of masses in the theory break the conformal invariance of the theory. However, above the electroweak phase transition the Higgs expectation value vanishes (cf. eq. (9)), which translates into zero rest masses of all the fundamental quarks, leptons and massive force mediators in the standard model.[65] The equations of the standard model will then remain invariant under the conformal rescaling.

> **Observation #4:** *There is no physical basis for the time scale if only conformally invariant material is available.* If there is scale invariance of the available physics above the electroweak phase transition it will be impossible to find physical processes (among the microphysical constituents) which can set a fixed scale.

This would imply that we cannot even in principle find a core of a clock among the microphysical constituents of the universe at this early stage: The relevant physics (the electroweak and strong sector) cannot set physical scales for time, scales for length and no scale for energy. If there is no scale for length and energy then there is no scale for temperature T. Metaphorically speaking, we may say that not only the property of mass of the particle constituents 'melts away' above the electroweak phase transition but also the concept of temperature itself 'melts' (i.e. T loses its physical foundation above this transition point).

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symmetry).

[64]For example, the concept of temperature transforms as energy, $T \to 1/\lambda\, T$, and the concept of energy density $\rho = E/V$ transforms as $\rho \to (1/\lambda^4)\, \rho$, etc.

[65]In finite temperature QFT there are temperature corrections to the rest masses, but the masses which 'effectively' arise in this way will be proportional to the temperature T and will thus not be able to set a fixed scale which can provide a physical basis for T itself. The Higgs mass itself has a slightly more complicated story. Above the phase transition m_{Higgs}^2 has contributions from a (tachyonic) mass term $m_0^2 < 0$ as well as the finite temperature T contribution. It is unclear to us whether such a mass term can be associated with some physical process which could function as the core of a clock. In any case, well above the phase transition the effective Higgs mass will (again) be proportional to the temperature T. So, in the 'desert' well above the phase transition the high-T effective Higgs mass will not be able to provide a physical foundation for the temperature concept itself.

We remark that Roger Penrose (2006) has recently pursued ideas about (the lack of) time in a conformally invariant universe which are similar in spirit to our discussion (above and in previous versions of this manuscript). Cf e.g. (2006, p. 2761):

> With [...] conformal invariance holding in the very early universe, the universe has no way of "building a clock". So it loses track of the scaling which determines the full space-time metric, while retaining its conformal geometry.
>
> [...] the universe "forgets" time in the sense that there is no way to build a clock with just conformally invariant material. This is related to the fact that massless particles, in relativity theory, do not experience any passage of time.

In spite of the similarity with our discussion, however, Penrose appears to assume the necessary link between time and clocks without providing further argumentation.[66]

In the following we mention some possible avenues which should be pursued in order to introduce the concept of scale to this seemingly scale invariant physics and thus possibly provide some (micro-)physical underpinning of cosmic time beyond $\sim 10^{-11}$ seconds. We are acquainted with three mechanisms which can break the perfect scale symmetry:

(1) The dimensionless coupling constants $\alpha = \alpha(\mu)$ run with the energy scale μ (quantum anomalies).

(2) Gravitational interactions break the scale invariance.

(3) New speculative physics may introduce length and time scales.

A detailed discussion of these options involves complicated physics beyond the scope of the present manuscript.[67] Thus we only present some very brief remarks here.

As concerns (1), the running of the coupling constants (of the various gauge theories) is an effect of higher-order corrections in quantum field theory (a quantum 'anomaly').[68] One might imagine scattering experiments (thought experiments) in the early universe which could determine various values of α, and then one could imagine that these values, together with theoretical knowledge about the running

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[66]Whereas we attempt in the present manuscript to initiate a systematic study of the physical basis of time, the context of the quote is Penrose's proposal of an "outrageous new perspective" (a conformal cyclic cosmology) in which approximate conformal invariance holds in both ends (the beginning and the remote future) of the universe.

[67]We are currently investigating such attempts to base the conception of time beyond the electroweak scale in collaboration with H.B. Nielsen.

[68]This running is extremely small for the electromagnetic running coupling constant: $\alpha_e = e^2/(\hbar c)$ runs from 1/137 at zero energy density, to $\sim 1/128$ at the electroweak scale to $\sim 1/110$ at the Planck scale. The running is more substantial for the strong coupling constant which is large at low energy density (non-perturbative QCD) and small at high energy densities (the regime of perturbative QCD), cf. the notion of 'asymptotic freedom'. However, the parameter $\Lambda_{QCD} \sim 0.2$ GeV which separates these regimes is more than a factor one thousand smaller than the energies and temperatures in question (above the electroweak phase transition point).

of $\alpha = \alpha_g(\mu)$, could be turned around to extract the energy scale μ. However, our preliminary finding is that physical scales will be needed as 'input' (rather than being derivable as output) in order to specify the set-up of such experiments. This suggests that the running of coupling constants in itself is insufficient to provide a physical foundation of scales in the very early universe.

As concerns (2), the gravitational interaction stands out (as compared to the three other coupling strengths for the electroweak and strong interactions) since it has dimension: $G = 6.67 \times 10^{-11} m^3 kg^{-1} sec^{-2}$. According to general relativity, gravity couples to the total energy, not just to rest mass, and it is standard to provide a dimensionless measure of the strength of the gravitational coupling as given by

$$\alpha_g = \alpha_g(\mu) = \frac{G\mu^2}{\hbar c^5} \tag{11}$$

In this way a running of the (dimensionless) gravitational coupling constant with the energy scale μ is introduced.[69] The coupling constant runs from the extremely small values $\alpha_g(\mu = m_p c^2) \sim 10^{-40}$ at the energy scale of the proton mass up to order unity at the Planck scale, $\mu = E_P = (\hbar c^5/G)^{1/2} \sim 10^{19}$ GeV. Since the strength of the gravitational coupling constant is so extremely tiny at scales of ~ 1 GeV ($\alpha_g(\mu = m_p c^2) \sim 10^{-40}$), it is standard to assert that the gravitational interaction is simply totally negligible in the realm of elementary particle physics.

Introducing the gravitational constant in the problem will of course yield a scale (since G carries a mass scale with it – when it is combined with $\hbar$ and c). However we are suspicious of the scales (Planck scales) introduced by the way of constants of nature, if these cannot be associated with possible or actual physical processes at the time. Theories of quantum gravity are still highly speculative, and moreover there are well-known problems of even identifying a suitable time parameter in such theories. In any case it is expected that quantum gravity effects are negligible at energy scales around the electroweak phase transition point (and negligible well into the 'desert' above this phase transition). On the other hand, the *classical* gravitational field couples to radiation in the sense that the expansion of the universe (as described by a scale factor $R = R(t)$) yields corresponding redshifts in the radiation field. However, if the universe merely consists of radiation (and massless particles) with wavelengths which expand at exactly the same rate as the overall scale factor, then 'expansion' appears to be a physically empty concept (without a physical basis), cf. the discussion in section 4.1. Thus, if the microscopic structure of matter is scale invariant it might not be possible to obtain a length scale from the interplay of (scale invariant) microphysics with gravity; cf. also the Eddington remark quoted in section 2.

After this short discussion of the role of gravity in setting a length scale, we turn in the following subsection to the third option for breaking the scale invariance.

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[69]In contrast to the gauge theory coupling constants, the running of the gravitational coupling constant is a trivial one: The gravitational constant G has dimension, and thus runs with a change of scale (not as a result of renormalization group equations within the framework of QFT).

5.5 Beyond the standard model

The standard model is expected to be just some 'effective' theory arising from a more fundamental theory with built-in constants and parameters referring to higher energies than the parameters of the electroweak standard model (governing the electroweak phase transition described in sec. 5.4).

Massive X particles populating the 'desert'?
The standard model involves roughly 20 unexplained 'input' parameters. Grand unified theories (with a unification mass scale M_X) have been constructed with the purpose of explaining the values of some of these input parameters. In the simplest possible SU(5) GUT theory the experimental bound on the proton lifetime implies that the new X particles in the GUT theory have masses $M_X \gtrsim 10^{14} - 10^{15}$ GeV (only 4 orders of magnitude below the Planck scale) and there will be a 'great desert' with no new physics between the scales of the electroweak scales ~ 300 GeV and the M_X scales (Froggatt and Nielsen 1990, p. 47). Such a scenario with no new particles over 12 orders of magnitude in the roughly scale invariant physics is not good news for finding physical processes comprising the cores of clocks.[70] Rather it implies a 'great desert' (from ~ 300 GeV to $\sim 10^{14}$ GeV) for which the remarks about scale invariance (and the lack of physical length scales) of subsection 5.4 apply.[71]

If the time scale concept is to be founded upon the introduction of speculative massive particles, we have an example of the following:

> **Observation #5:** The time scale above the electroweak phase transition is purely speculative in the sense that it cannot be founded upon an extrapolation of well known physics (due to scale invariance, section 5.4) above the phase transition point. Thus time (the time scale) will have to be founded on the introduction of new physics (beyond the standard model of particle physics), and is in this sense as speculative as the new (speculative) physics on which it is based.

Time of inflation: $\sim 10^{-34}$ seconds?
Whereas inflation in its original conception was tied to (speculative) GUT theories, spontaneous symmetry breaking (phase transitions), etc. – thus providing a bridge between speculative high energy physics and cosmology – this link between inflation and particle theories has become weaker in subsequent developments (see also e.g. Zinkernagel (2002)). Inflationary models often introduce a species of massive scalar

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[70]However, it has recently been (optimistically) contemplated that the onset of string theory, and therefore of quantum gravity, could occur already at a scale much lower (around $\sim 10^3$GeV ~ 1TeV) than the Planck scale. This would imply that the time (and space) concept would be severely modified (if at all meaningful) already at times corresponding to TeV scales (see e.g. Antoniadis et al. (1998)).

[71]Other more complex grand unified theories can be constructed (see, e.g., Collins et al. 1989, p. 164). Supersymmetric model building is another proposal for physics in the desert in which each particle is paired with a superpartner (yet to be observed), and such models thus introduce plenty of new (speculative) particles.

fields ϕ and potentials $V(\phi)$ accompanied by various adjustable parameters which are only weakly linked to known (or speculated) physical processes. If the parameters of some inflationary model are adjusted so the duration of the inflationary phase is '10^{-32} seconds', say, it appears that such an interval of time is put into the model – by hand – via the fine-tuning of various mathematical parameters of the toy-model, and not set by time scales of microphysics. It is our suspicion that such procedures provide a rather weak physical basis for the time scale concept.[72]

The space-time metric (usually) envisaged in the inflationary phase is the de Sitter metric, which is a spatially homogeneous and isotropic solution to the Einstein equations for an empty space with a vacuum density (cosmological constant) Λ. Some researchers speculate that the particle content of the universe was first created with the inflationary reheating.[73] In this case, one will have to physically ground the time (and length) scale concept 'during' inflation on a scalar field (acting as a cosmological constant). Whereas such ideas may introduce length scales in the envisaged early inflationary universe, the ideas remain of course speculative and the time scale concept based upon various physical processes which may take place in the inflation 'epoch' (e.g. the time scales associated with various oscillations in the ϕ field) is likewise speculative. (The introduction of a massive scalar (inflaton) field ϕ bears some resemblance to the introduction of speculative X particles mentioned above).

In the (much studied) class of inflationary models known as "chaotic inflation" (Linde (2004)) it is of interest to note that it is necessary to require that the initial value of the inflaton field *exceeds* the Planck scale (see e.g. Peacock (1999), p. 336-337)

$$\phi_{start} \quad \gg \quad m_P = (\hbar c/G)^{1/2} \sim 10^{19} \text{ GeV}/c^2$$

Thus, not only do such envisaged mathematical scenarios involve extrapolations of our physics framework (quantum field theory and general relativity) down to Planck scales – but even substantially beyond Planck scales and right through the 'era' of quantum gravity – where it is a widely held view that the concepts of space and time lose their meaning.

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[72]We note that it is sometimes asserted that inflation starts 10^{-34} seconds 'after' the big bang, and, moreover, that inflation is contemplated to have observational consequences. For instance, it is speculated that the nearly scale invariant spectrum of cosmological perturbations observed in the cosmic microwave background radiation (cf. the COBE and WMAP experiments) could have been created during inflation as far back as the quoted $t \sim 10^{-34}$ seconds, and that those cosmological perturbations subsequently propagated, almost uninterruptedly, through the hot early universe plasma – over an interval of time which spans 47 orders of magnitude! – up to the times of the release of the CMB $\sim 10^{13}$ seconds after the big bang.

[73]Cf. e.g. Linde (2004, p. 454): "All matter surrounding us was produced due to the decay of the scalar field after inflation. [...] All matter in the universe was produced due to *quantum* processes after the end of inflation".

6   Summary and concluding remarks

In section 1 and 2 we point out that cosmology implies a tremendous extrapolation of our ordinary concept(s) of time (and space). Nevertheless, we argue that the concept of time in cosmology, as well as in ordinary language, should be understood in relation to physical processes which can serve as (cores of) clocks. Our position is in conformity with a *relationist* view of space-time in the tradition of philosophers like Leibniz, although the relationism we defend is not reductionist – that is, we maintain that time and physical processes which can serve as (cores of) clocks are equally fundamental. In the cosmological context we attempt to motivate, within the scope of the time-clock relation, the criterion that in order to interpret t of the FLRW model as time, that is, in order for cosmic time to have a physical basis, it must be possible to construct a core of a clock out of the physics envisaged in the various epochs of cosmic history. In particular, we maintain that in order for the cosmic time *scale* (used to indicate the onset and/or duration of the various epochs) to have a physical basis, the physical process acting as a core of a clock must have a well-defined duration and must be sufficiently fine-grained to 'time' the epoch in question.

In section (2 and) 3 we argue in favor of the necessity of rods and clocks in the theories of relativity and cosmology (e.g. for setting up the FLRW reference frame). We note in particular that the classical gravitational field in general relativity, by itself, is not able to set any length or time scales (the combination of c and G is insufficient to set such scales). General relativity has to 'go outside its own borders' and obtain such scales from the material content (providing the cores of rods and clocks). We indicate also how the empirical adequacy, and the very formulation of, the simplifying assumptions in standard cosmology (the Weyl principle and the cosmological principle) depends on physically based scales.

In section 4 and 5 we analyze possible clock systems (physical processes which may function as the cores of clocks) in the early universe and find that they all depend on the existence of physically founded scales (e.g. the spatial extension of bound systems). For instance, we see that the concept of temperature – which is the most commonly used time indicator in the early universe – rests on the existence of sufficiently fine-grained and physically based length and energy scales. We note that such physical scales – in order to be non-speculative – should be based on well-known physics available at the cosmological epoch in question. This alone suggests that the cosmic time (scale) concept becomes speculative 'before' 10^{-11} seconds – corresponding to energies (~ 300 GeV) indicating the current upper limit of known physics (the standard model of particle physics).

Speculative physics is needed not only because presently known physics is too 'coarse' – and thus unable to provide sufficiently fine-grained physical scales to ground concepts like time, length and temperature in very 'early' epochs. As we discuss in section 5, within known physics the existence of *any* physical scale (fine-grained or not) gradually becomes more questionable as the temperature increases in the very early universe. In this regard, we emphasize two important 'moments':

(i) above the 'quark gluon' phase transition, at $\sim 10^{-5}$ seconds there are roughly no bound systems left (liberation of quarks); and (ii) above the electroweak phase transition, at $\sim 10^{-11}$ seconds all the fundamental constituents of the standard model become massless. When all masses are zero, the gauge theories describing the material constituents and their interactions are (locally) scale invariant, and thus the material content of the universe cannot set physical scales for time, length and energy.[74] If there are no scales for length and energy then there is no scale for temperature T. We have formulated this observation in the following metaphorical form: Not only the property of mass of the particle constituents 'melts away' above the electroweak phase transition but also the concept of temperature itself 'melts' (i.e. T loses its physical foundation above the phase transition point).

These results suggest that the necessary physical requirements for setting up a comoving coordinate system (the reference frame) for the FLRW model, and for making the $t \leftrightarrow$ time interpretation, are no longer satisfied above the electroweak phase transition – unless speculative new physics is invoked. The physical requirements include the (at least possible) existence of (cores of) rods and clocks as well as the validity of the Weyl postulate. If there are no length scales set by the material constituents above the electroweak phase transition then the concept of a rod (like that of a clock) will become unclear. As concerns the Weyl postulate, this involves the idea of non-intersecting particle trajectories, often envisaged to be the world lines of galaxies which are at rest in the comoving frame. For massless particles with random movement at velocity c, the Weyl postulate is not satisfied for a typical particle, although one may attempt to introduce fictitious averaging volumes (which thus require a length scale) in order to create as-close-as-possible substitutes for 'galaxies which are at rest'.

The role of time is a main topic in contemporary studies of quantum gravity and quantum cosmology. We nevertheless hope to have made plausible in the foregoing that there are interesting problems with establishing a physical basis for the concept of time, and in particular for the concept of a time scale, in cosmology much (thirty orders of magnitude) before theories of quantum gravity may come into play.

If it is correct that time is necessarily related to actual or possible physical processes in the universe, then what are the consequences for early universe cosmology? Although our considerations suggest scepticism concerning the reliability of the FLRW model before the electroweak phase transition, we do not imply that early universe cosmology should abstain from investigating mathematical models which could be relevant for our understanding of cosmic history. Rather, our analysis suggests that any speculative model for the very early universe imagined to be operative at some specific 'time' ought to include considerations concerning what kind of physical processes could be taken to physically ground the time (scale) concept. But given that these processes are based on speculative physics, it should

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[74]As mentioned in section 5.4, some small quantum anomaly effects as well as the force of gravity are known to break this scale invariance, and it will be important to study if physical length scales (which refer to contemplated physical processes in existence at the time) can be based on those symmetry breaking effects (or if new speculative physics has to be introduced in order to set appropriate physical length scales).

be admitted that the time (scale) concept will be speculative as well. As a more general conclusion, we hope that this study of time contributes to a clarification of the physical foundations of modern cosmology.

Acknowledgements

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