Cosmic Simultaneity

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Einstein claimed that various phenomena synthesised by his Special Theory of Relativity had the consequence that 'we cannot attach any absolute signification to the concept of simultaneity, but that two events which, viewed from a system of coordinates, are simultaneous, can no longer be looked upon as simultaneous events when envisaged from a system which is in motion relatively to that system.'[2] I argue in this paper that Einstein gave good, but not compelling grounds for supposing that the concept of absolute simultaneity would have no application in a universe empty of matter and so governed entirely by the laws of Special Relativity. But I claim that there is absolute simultaneity in our homogenous and isotropic universe of galaxies receding from each other with a metric described by the Robertson-Walker line element. 'Cosmic Time' provides a correct standard of absolute simultaneity.

I

It is important to distinguish between an analysis of the nature of a concept, and primary and secondary tests for its application. An atom of (uncharged) hydrogen just is an atom consisting of one proton and one electron. But sometimes concepts are too basic to be analysed; 'cause', 'property' (in the philosophical sense), and 'colour' are like this. One can merely illustrate by examples cases of one thing or event causing another and show some of the entailments thereof (e.g.that if A causes B, then B does not cause A). The primary tests for the application of a concept are the best tests anyone could ever use –given the physical laws by which the universe is governed. Where the concept can be analysed, the primary tests are constituted by the analysis. The test that an uncharged gas is hydrogen is that it consists of atoms each consisting of one proton and one electron. But where the concept cannot be analysed, there are still primary tests.

is a primary test for the value of some property, e.g. the distance between two points, if it is a member of a set of tests , , , etc., such that if the use of all those tests gives one definite value for the property, then the value given by those tests is the best possible estimate of the value of the property. No different tests can upset the common result of all the primary tests. □ is a secondary test for the value of a property, if we only use it because we have good reason to believe that it would give the same result as one or more primary tests if we were able to use the latter. If a secondary test gives a result different from that given by the primary tests, the former is considered wrong and the latter right. If different primary tests give in some particular situation different results from each other, then we cannot estimate reliably the value of the property. But we must distinguish between two cases – one where the primary tests give an analysis of the concept of the value of the property, and the other where they do not but are still the best tests anyone could ever have for that value. In the former case the different results given by the different primary tests show that the concept of that property having a definite value does not apply in this situation; in the latter case the different results show only that we can never know what the value of the property is in this situation. And if with respect to all situations different primary tests give different results for the value of some property this may be either because the concept of it having a value has no application, or because there are limits to the possibility of human knowledge of what that value is.

Thus in my view (for which I do not argue here) the spatial distance between two points can be analysed in terms of how many rigid rods which coincide with each other at one place, can be laid between the two points; and the rigidity of a rod can be analysed in terms of it continuing to coincide with the members of the only family of rods which preserve coincidence relations with each other. There is no content to the concept of a distance between two points apart from what would be measured by such rods. Hence in this case the primary tests for the application of the concept are provided by an analysis of the concept. But for distances of any magnitude it is not in practice possible to lay down rigid rods, and so we have to use the secondary tests of stellar parallax, apparent luminosity of Cepheid stars, red shift etc.

II

With these points in mind, and before coming explicitly to discuss the concept of simultaneity at different places, I need to consider the criteria for measuring temporal interval at any one place, the 'proper time' at that place as it is often called. Places are places on a frame of reference, that is an extended system of physical objects (normally material objects) stationary relative to each other. Frames of reference move relative to each other, and an object stationary in one frame may be in motion relative to another. A book on a car seat will be stationary relative to the car, but may be in motion relative to the Earth. Scientists seek the simplest laws of nature yielding the most accurate predictions. Any law of nature can be formulated in various different ways, simple or complicated; but the simplicity of a law of nature depends on the simplicity of the simplest way of formulating it. Laws of nature involve assertions about forces arising from distances between objects; and they can be expressed most simply if these distances are measured relative to some frames of reference rather than others. A frame of reference relative to which the laws of nature can be formulated most simply I shall call a basic frame. There might in principle be either many such equally basic frames (equibasic frames), or just one unique one.

In a space empty of matter there is (or can be constructed) a class of equibasic frames called 'inertial frames' which are such that when measurements of distance are made relative to these frames Newton's laws of motion hold with perfect accuracy. Every different inertial frame moves with uniform velocity relative to every other inertial frame. Most small regions of the Earth's surface are near approximations to an inertial frame.

How then is temporal interval to be measured on an inertial frame such as (approximately is) the surface of the earth? To say that an event occurred n units of time after another event at the same place is to say that if a true clock recorded a certain reading at the instant of the occurrence of the first event , then it would record a reading greater by n units at the instant of the occurrence of the second event. Statements about temporal interval are statements about what would have been or would be recorded by true clocks. A clock measuring intervals in terms of one kind of unit, say hours, will measure time on the same time scale as another clock measuring intervals in terms of another kind of unit, say minutes, if all measurements of intervals between any two events by the two clocks are linearly related to each other; that is, each measurement by one clock in terms of its units is a constant multiple of the measurement of the same interval by the other clock in terms of its unit. A clock with only a minute-hand and a clock with only an hour-hand measure time on the same time scale.

But what is it for a clock to be a true clock? Any actual recurrent process – the rotation of the Earth, its revolution around the Sun – forms a clock, and yields a potential time scale whereby we can measure intervals. So too does any mechanical device which could be built – such as a pendulum clock – in which there is a recurrent process. Every occurrence of the process or some function thereof is assumed to occur after the same period of time, and we call this interval between any two occurrences – provisionally – a time unit. The rotation of the Earth takes a day. This gives us units in terms of which we can measure processes. If we assume that the Earth rotates at a regular rate against the background of the 'fixed' stars, we can divide the day into hours and minutes and seconds. On this basis we may postulate laws of nature describing how bodies move under the influence of forces of various kinds.

There are two primary tests for a potential time scale to be a true time scale (that is for the measurement made by a certain clock to measure the passage of time correctly). The first test is that judgements of temporal interval yielded by that scale between events which form part of our history and in particular of our personal experience must not diverge radically from those which we ordinarily make by means of the day and year scales which have been in use for so many thousands of years. Two events on Earth on different days which last from when the Sun is at its highest point in the sky one day to when it is at its highest point the next day must be said to last approximately the same period of time as each other. So too must two events in different years from when the Sun is in Capricorn to when it is in Capricorn the next year. For if the adoption of a proposed time scale meant that last sidereal year was a thousand times longer than the previous sidereal year, that time scale could not be adopted – however simple the resulting laws of physics . This is so because such expressions as 'equal time interval', 'much longer time', etc., are given their meaning by the circumstances in which ordinary users of language judge it appropriate to use them. We only know what these expressions mean because we have been taught what these circumstances are. If physics radically contradicted all such obvious common-sense judgements about time intervals, we would have to conclude that it did not use 'time' in the same sense as did ordinary language. Certainly some law of physics may be simpler if the 't' in it is said to be a thousand times greater for last sidereal year than for the preceding one. But if we are to say that 't' denotes time, our judgements of t-interval must correspond largely to the judgements of time interval which would be made in ordinary circumstances of personal experience and familiar human history by an ordinary user of language. Otherwise why say that the physicists' 't' denotes time?

The first test for a clock measuring the true time scale is a criterion which clocks need satisfy only approximately. Subject to it the second primary test is that the true time scale at any place is that which will give the simplest form to the laws of nature. Our ground for not choosing a typical medieval town clock as the true timepiece is that, if we used it, we would have to postulate highly complex laws of nature. These laws would have the consequence that days were of uneven length, and so the Earth would be rotating at a significantly ever-varying rate. Bodies would attract each other with forces of intensity varying from instant to instant. The principle that the scientist should choose from among proposed laws compatible with observed phenomena the simplest possible leads to the rejection of such a time scale. The reason why – in my view – scientists choose the simplest proposed laws yielding the most accurate predictions is that such laws are more probably the true laws than are more complex laws; and – in my view – they are right so to think[3]. Hence the time scale used in them is that most probably true. If we choose the scale given by the daily rotation of the Earth relative to the ‘fixed stars’ we find that bodies obey Newton’s three highly simple laws of motion and the simple inverse square laws of gravitation and electrostatic and magnetostatic attraction to a high degree of accuracy; and obey the comparatively simple laws which give better predictions of phenomena, such as Einstein’s field equations and the laws of Quantum Theory – to an even higher degree of accuracy.

Once upon a time the ‘daily rotation’ scale provided the official scale for measuring temporal interval. This was then replaced by the ‘annual revolution’ scale, and in 1966 the ‘annual revolution’ scale was replaced by a scale based on the natural frequency of radiation of a line of caesium[4]. The role of each new definition has been marginally to correct and not to replace the previous method of measuring temporal interval; and the grounds for adopting each new definition were that it had the consequence that what we reasonably believe to be the true laws of nature predict even more accurately. The true scale is that which would be used in the true laws of nature. The time scale which is most probably (on our present evidence) the true scale is that which is used in what are most probably (on our present evidence) the true laws of nature. That the frequency of radiation of an atom of a given kind is constant is most probably (on our present evidence –but see note 4) such a true law.

My account of our grounds for adopting the particular time scale which we do are grounds arising from the behaviour of material bodies and of electromagnetic radiation on Earth, and are therefore grounds for adopting it for judging proper time on Earth. But since there is good reason (which I shall discuss briefly later) to suppose that the same fundamental laws of nature operate at all other places in the universe as operate on at places on earth , time at any place in the universe is to be measured by a clock based on the same scale – e.g. the radiation frequency of caesium there. But do these two primary tests analyse the concept of temporal interval, or are they simply the best tests we can have (given the actual laws of nature) for the applicability of a concept too basic to be exhausted by the results of our human tests? We can see the answer to that by asking ourselves what we would say if there was not at any place any unique simplest time scale such that if measurements were made by it all laws of nature would predict with perfect accuracy everywhere.

E.A. Milne once suggested that electromagnetic phenomena could best be dealt with by his t-scale, and dynamical processes by his t-scale, and that these scales were related asymptotically.[5] Fortunately science has found no need to adopt his suggestion. But if we found that Milne's suggestion was correct, would we say that there was a true temporal interval between two events but we could never know what it was; or would we say that the only fact of the matter was that between any two events there was one interval measured by one scale and a different interval measured by another scale? Would we say, for example, that the interval between t_1 and t_2 was a certain number of times as long as the interval between t_0 and t_1 but we could never know how many; or that it was of the same length as the latter interval by one scale and twice as long by another scale and that there was no one true scale? For myself I cannot give any content to the former suggestion. I cannot understand what would be meant by there being a true time scale independent of what instruments showed; and so I am inclined to say that the primary texts for temporal interval at one place analyse the nature of the concept. A major reason why I am inclined to say this is that it is not merely physically impossible, but logically impossible to have a better way of judging whether two non-overlapping temporal intervals are of equal length than by seeing whether (subject to satisfaction of the first primary test) that result follows from using clocks which give to the true laws of nature their simplest form.[6] It is not logically possible to move one of these intervals adjacent to the other and check whether they coincide! But since all the evidence is that at each place there is the same unique best way of measuring temporal interval, it shows that there is in fact a unique correct true time scale. So I suggest that we agree with Newton that there is an 'absolute, true, and mathematical time'; but I suggest that this is a contingent truth and, contrary to Newton, that time does not 'of itself and from its own nature, [flow] equably without relation to anything external'.[7] Conventionalism about temporal interval at any one place[8] is false, but only contingently so.

The primary tests for temporal interval give rise to secondary tests such as those which ascertain the age of objects from the percentages of radioactive substances contained in them. We find the proportion of atoms of substances which decay in some period of time, as measured by our best clocks, viz. by primary tests; and so assuming the same rate of decay to operate at all temporal periods we find the half-life of such substances, viz. the expected value of the period of time in which half of some mass of a substance will decay. We find that two isotopes of Uranium, U^{238} and U^{235} decay respectively into isotopes of lead Pb^{206} and Pb^{207} with half-lives of 4510 and 707 million years. We then infer how rocks containing uranium are formed and so infer the relative proportion of these isotopes of uranium and lead to be expected in the Earth's rocks on their first formation. Then from the proportion of the different isotopes of lead to the different isotopes of uranium currently found in rocks, we calculate their age. This method utilizes primary tests to measure the rates of decay over a few years, and generalizes that the same rates of decay will hold over millions of years where we cannot in practice use the primary tests, because then were there no observers who could have measured the passage of time by clocks. Having illustrated, for temporal interval at one place, what constitutes a secondary as opposed to a primary test, I shall not bother to discuss secondary tests for the main temporal concept which I am about to discuss, simultaneity at different places, since it should be clear by now what the contrast between primary and secondary tests amounts to. My interest is solely in primary tests.

III

So much for time at one place. What are the criteria, the primary tests, for an event at one place occurring at the same time as a certain event at another place? How, that it, can we synchronize a clock at one place so that it records a certain time at the exact instant when a clock at another place records that time? We can synchronize clocks at the same place simply by adjusting them to record the same temporal instant, as they touch each other. Synchronisation at the same place I shall term direct synchronisation. Synchronisation at two distant places I shall term indirect synchronisation. Intuitively, before we introduce any modern science, there would seem two possible methods of synchronising clocks at distant places P and Q, the clock-transport method and the signal method. The clock-transport method is to have two clocks at P synchronized with each other directly at t_0 and then move one of them to Q; when it reaches Q at say t_1 you synchronize the clock at Q with it directly. The signal method is to send a signal at t_o from P to Q. It arrives at Q at t_1. Immediately it arrives the signal is sent back from Q to P where it arrives at t_2. Now t_1 must lie between t_0 and t_2 by the principle that causes necessarily precede their effects. We then make the simplest hypothesis about the velocity of the signal coherent with the rest of physics. This hypothesis will yield a solution about where t_1 lies between t_0 and t_2, and hence provide a procedure for synchronising clocks at P and Q. The observer at P can then tell the observer at Q that the signal was sent at 't_o' and received back at 't_2' by P's clock, and the observer at Q can then set his clock so that by that clock the signal would have arrived at Q at the time intermediate between t_o and t_2 dictated by that simplest hypothesis.

It would seem that, whether or not they analyse the concept of simultaneity, one or other of these methods or perhaps both of these methods taken together are the primary tests for synchronising clocks at different places. A clock at P and a clock at Q will show the same time if a clock transported from P to Q, showing the same time as P's clock on departure, shows the same time as Q's clock on arrival; and if a signal sent from P to Q and back again arrives at Q at the instant on P's clock, predicted by the simplest hypothesis coherent with the rest of physics about the velocity of the signal and information about the instants at which, by P's clock, it left P and returned to P. (Time at each place is to be measured by true clocks, identifiable as such by the methods described in the previous section.)

Unfortunately it is a physical fact that different applications of each method conflict with each other and with applications of the other method in some circumstances. First, take the signal method. A signal is sent from P to Q and back again. The time of its arrival at Q, t_1 on Q's clock, must lie between t_0, the time of its departure from P, and t_2 the time of its return to P. If we had a signal which returned to P in less than any finite period of time and so had infinite velocity, we could uniquely identify t_1. For then (if we ignore any infinitesimal intervals) $t_1 = t_0 = t_2$. No such signal is known to science. In the absence of one, it is clearly desirable to choose the signal with the fastest two-way velocity, that is a signal whose total journey there and back is the fastest. For such a signal will narrow down the possible values of t_1 as much as possible. The fastest signal known to physics is that of light and all other electromagnetic radiation, which has -at any rate within the region of our galaxy – a mean or two-way velocity of approximately 300,000 km/sec (denoted by c). (We cannot of course measure the one-way velocity of light, i.e. its velocity relative to P on its journey from P to Q, without having first synchronised a clock at Q with one at P.) Now light (and all other electromagnetic radiation) has the peculiar property not shared by material objects that its mean velocity has the same value in all inertial frames. By this is meant that when a light signal is sent between any two points P and Q and back again (stationary or in motion relative to each other), and that passage is marked as a passage on an inertial frame moving relative to P or Q with any velocity, then the mean velocity of the signal will be the same in all such frames.

That the mean velocity of light has the same value (c) in all inertial frames is the most natural extrapolation from a very large number of experimental results, the most celebrated of which is the Michelson-Morley experiment. The most natural simplification of this extrapolation is that the signal has in every inertial frame its mean velocity as its one-way velocity relative to the source in every direction,

viz $t_1 = \frac{t_0 + t_2}{2}$. Since, as we have seen, science aims to formulate the simplest laws of nature compatible with phenomena, the assumption must be adopted – unless it leads to complexities elsewhere. It does not initially lead to any such complexities.

Given this assumption that the one-way velocity of light is the same as its two-way velocity (c) in all inertial frames, Einstein derived as the fundamental hypothesis of Special Relativity the 'Lorenz transformations' which relate measurements of time and distance in different inertial frames to each other. If an inertial frame $F^{/}$ is moving with uniform velocity v along the x-axis relative to inertial frame F, then an event at (x,y,z,t) in the frame F will have coordinates $(x^{/},y^{/},z^{/},t^{/})$ in $F^{/}$ (the first three coordinates being Cartesian spatial coordinates and the last coordinate the temporal coordinate, spatial and temporal origin points being the same for measurements in both frames) such that:

$$x' = \beta(x - vC)$$

$$y' = y$$

$$z' = z$$

$$t' = \beta(t - \frac{vx}{c^2})$$

where:

$$\beta = \frac{1}{\sqrt{1 - \frac{v2}{c2}}}$$

Spatial distances are measured by rods in the way briefly described earlier. So $x^{/}$ is the distance measured in this way by rods in $F^{/}$ between two events whose distance apart measured in F in the same kind of way is x. t is the temporal interval between these events as measured by the signal method and true clocks in F, whereas $t^{/}$ is the temporal interval between the same events as measured by the signal method and true clocks in $F^{/}$ –all measurements being made on the assumption that the one-way velocity of light is the same in all frames. For clocks on the same frame of reference (that is, for clocks stationary among themselves), these two temporal values (t and $t^{/}$) will be the same. The signal method provides an unambiguous way of synchronizing clocks at different places in the same frame; and using it provides confirmation that natural processes run at the same rate at each place on any one frame. These processes include, as well as the radiation frequency of a line of caesium, biological growth and decay.

Yet for events on frames moving relative to each other, the signal method gives different results for the interval between two events, according to the frame on which the measuring clocks are situated. Consider two events E_1 and E_2, say flashes of lightning. It is a consequence of the Lorenz transformations that if E_1 and E_2 are simultaneous as judged by the light signal method used in F, they will not be simultaneous as judged by the light signal method used in F', and conversely. For, if the time interval between E_1 and E_2, as judged in F, is t =0, then the time interval between them as judged in F' will be

$$t' = \frac{\beta v x}{c^2}$$

Conversely if t', the time interval c^2 between E_1 and E_2 as judged in F', = 0,

$$t = \frac{v x'}{\beta c^2}$$

Consequently the signal method for synchronising the clocks leads to inconsistency. For if it is valid, you find of two events that they both are and are not simultaneous. The relativity of simultaneity, as judged by the signal method, is, as we have seen, predicted by the Special Theory; but the formula:

$$t' = \beta - \frac{vx}{c^2}$$

has been well confirmed independently.

Exactly the same problems arise with the other method for synchronizing clocks – the clock transport method. It follows from the Lorenz transformations that a clock taken from P to Q and then brought back to P will have slowed down by P’s clock, the difference between the two clocks being greater, the faster the moving clock is moved (relative to P). But if P and Q are on the same reference frame (that is, stationary relative to each other), and the moving clock is moved slowly, the difference between the clocks is going to be very small. We can work out the limit of this process – that is, to talk slightly metaphorically, what the clock would read if it were moved infinitely slowly; and then directly synchronize the clock at Q with the moving clock corrected for what it would have shown if its motion had been infinitely slow. We then move the moving clock back from Q to P, and again correct its reading for what it would have read if it had been moved infinitely slowly. That reading will exactly coincide with the reading on the clock which stayed at P. The simplest hypothesis is to suppose that the clock ticks at the same rate when moved from P to Q as when moved in the other direction. With this assumption, the moving clock corrected for infinitely slow motion will yield a correct measure of simultaneity for clocks on the same inertial frame.[9] But again if P and Q are on different inertial frames in relative motion the clock transport method will give different results for when clocks are synchronized, depending on which is the frame in which the velocity of the clock is measured. This is for the simple reason that a clock moving with a velocity which is infinitely slow relative to P will not be moving with a velocity which is infinitely slow relative to Q, and vice versa. So each method of synchronization gives different results for when two clocks on different inertial frames are synchronized, varying with the frame in which the measurements are made.

Faced with this problem, there are two possible reactions. The first reaction is to say that the two primary tests for simultaneity do not provide an analysis of the concept, but are merely the best tests we can use for its application. There is a truth about which events at one place are (absolutely) simultaneous with which events at other places, but what Special Theory has shown is that we cannot discover which these events are. That is, there is a true frame of reference F relative to which alone the signal and clock-transport methods of synchronization give unique true results. To hold this involves holding that it is only motion infinitely slow relative to F which does not slow down a clock; and that only in F is the velocity of a reflected light signal constant in both directions. In all other inertial frames it will have some velocity j (different for each frame) in a certain direction and

$$\frac{cj}{2j-c}$$

in the opposite direction, with intermediate velocities in intermediate directions. This will mean that its mean velocity for a two-way trip will be the same in all inertial frames, as observable. The reinterpretation of physics leading to a unique measure of simultaneity can be carried through perfectly consistently and with identical complexity for any choice of preferred inertial frame[10], (and given the applicability of the Special Theory, any non-inertial frame would be a less basic frame and so one which science ought not to use). But the trouble is, if we confine ourselves to the Universe of Special Relativity, viz. a Universe virtually empty of matter, that there are no grounds for choosing one inertial frame rather than any other as the preferred frame, since-as we have seen – all inertial frames are equibasic. So unless we have grounds for adopting a scientific theory other than Special Relativity, and on the basis of it for judging that some inertial frame is more basic than others, or that some different frame of reference is more basic than inertial frames, we have no grounds for making our measurements of simultaneity relative to one frame of reference rather than any other.

The alternative reaction adopted by Einstein and expounded in text-books on the Special Theory of Relativity is to say that the ordinary concept of simultaneity could only be applied if two events simultaneous by the light signal method (and the clock method, although this was not considered by Einstein and most others) in one frame were simultaneous in all inertial frames, and so we must substitute for it the concept of simultaneity in a frame. Two events are simultaneous in a certain frame if the clocks in that frame synchronised by the light signal (and clock transport) method show the same reading when the two events occur. So E_1 and E_2 may be simultaneous in F, but not in F^1. But no contradiction arises, since it does not follow from E_1 and E_2 being simultaneous in F that they will be simultaneous in $F^/$ or any other frame.

Now there are, I think, grounds for supposing that our concept of (absolute) simultaneity is more basic than the primary tests for its application; whereas by contrast, I claimed that there was no more to the concept of equal temporal interval at a place than was contained in the tests for its application. For it is entailed by an event at P being simultaneous with an event at Q that if a signal of infinite velocity were sent from P to Q and reflected back to P (and so arrived back at P after an interval less than any finite interval), the time of its arrival at Q would be (by P's clock and by any other clock, and ignoring infinitesimal differences) the same time as the time of its emission from P. It is merely the physical impossibility of there being such a signal which prevents our using this method. But that does not show any logical impossibility in the sending of such a signal; and so there is content to the notion of absolute simultaneity – that is, what would be shown by the use of such a signal. Special Relativity, it would seem, simply reveals a limit to what we can discover, not to what is the case. By contrast there is no logically possible thought experiment in the case of measuring equal intervals of time at one place which would give a better result than the primary tests described in Section II.

However the view that in a universe of Special Relativity, there is an undiscoverable time frame of reference involves postulating not merely that there is some truth physically impossible for humans to discover, but that nature as it were conspires against our discovering it. Nature ensures that light behaves in such a peculiar way that the evidence will always support equally each of an infinite number of hypotheses about which is the true frame. We would have to suppose that ‘Nature contains both deep asymmetries and compensatory factors which exactly nullify these asymmetries’[11] in the sense of preventing us from ever discovering them. Scientific laws will have simpler formulations if we do not have to postulate such a coincidental balancing arrangement. And that suggests that in such a universe, incomprehensible as it may seem, there would be no absolute truth about when on P’s clock the signal arrives at Q. While the existence of absolute simultaneity in the universe of Special Relativity is certainly logically possible, considerations of simplicity suggest that it would probably not exist there .

IV

However our universe is not on the large scale the Universe of Special Relativity. It consists, we now know, of galaxies of stars, grouped in clusters and superclusters. An observer on Earth notes that, on the evidence of their red shift and other secondary tests for distance, all other galaxies (apart from those very close to our own galaxy) are in recession from our galaxy; and that (when allowance has been made for some random clumping of galaxies) there are the same number of galaxies at any given distance in any direction from ourselves. All other such galaxies at any given distance in whatever direction have, when allowance is made for small random velocities, the same velocity of recession from our galaxy, a velocity which increases with distance (possibly uniformly but probably at an accelerating rate), viz, the observed region of the Universe is, relative to our galaxy, approximately isotropic. The isotropy of the Universe relative to ourselves is shown further by the fact that the temperature of the cosmic microwave background radiation (the presumed reshifted relic of the Big Bang) is to a high degree of approximation the same in all directions. Now is it only relative to our galaxy at this instant on its clocks that this isotropic recession of observed galaxies occurs, or does it occur relative to all other galaxies (observed and as yet unobserved) at all instants on the clocks of each? The principle of simplicity tells us (in the absence of counter-evidence) to postulate that for all galaxies at all instants on the clocks of each galaxy every part of the Universe is approximately isotropic (viz. galaxies at any given distance from any other galaxy- apart from any very close to it- are distributed uniformally and recede from it with approximately the same velocity). We can avoid the awkwardness that the isotropy is only approximate by postulating an imaginary frame of reference in the vicinity of each galaxy, relative to which the isotropy is exact- all other such frames at the same distance from it are distributed isotropically and recede from it with uniformly the same velocity. Such a frame I shall term a fundamental frame; and I shall follow the terminology of some of the literature of cosmology in terming an observer imagined as situated on such a frame a fundamental observer.A galaxy may rotate relative to its fundamental frame but any velocity of recession of the galaxy from the frame will be small, temporary, and equally likely to be in any direction.

The supposition that we can postulate associated with each galaxy a fundamental frame such that at any instant relative to it the Universe of mutually receding fundamental frames is isotropic, may be called the Principle of Isotropy. That it holds is an empirical postulate which might turn out to be false. For example, radio messages might one day be received from astronomers on a distant galaxy reporting that relative to them the observable Universe is very far from isotropic. But until such messages are received or other counter evidence is obtained, it seems correct to adopt the principle on grounds of that simplicity which is evidence of truth.

If then the observable Universe is always isotropic relative to each fundamental observer, it seems a further simplification to postulate that the laws of physics as formulated by an observer on each fundamental frame, using his measures of distance and clocks, are the same; and so that they are the same on each galaxy, if we make allowances for any random motion or rotation of the galaxy. This principle we shall call the Principle of Equivalent Laws. By this principle, if a clock of a certain construction is a true clock on some galaxy, then a clock of qualitatively the same construction will be a true clock on any other galaxy. There is detailed observable evidence that it holds on distant observable galaxies . We find that light spectra of elements on such galaxies have the same shapes as do the spectra of elements known to us shifted to the red, a shift which can be accounted for most simply by the recession of those galaxies from ourselves. It follows that the spectra of elements on such galaxies have the same shapes relative to each other as spectra of elements known to us, and hence an atomic clock graduated by the natural frequency of a line of one element there would ensure such simple laws of nature as the constancy over time of the frequency of light emitted by the other elements. And then the very regular behaviour of pulsars (spinning neutron stars emitting pulses of light which reach us at precise regular intervals, e.g. every 15 milliseconds) can be explained simply by supposing that the same laws of nature hold in their region as measured by its clocks, as hold in our region measured by our clocks; and so that pulsars are true local clocks.That all this continues to hold for galaxies too distant to be observed is the simplest extrapolation from the data.

It follows from the principle of equivalent laws that the fundamental frame in the vicinity of each galaxy is for the laws of cosmology an equibasic frame, viz. the laws of cosmology acquire their simplest form relative to any fundamental frame, but no fundamental frame is more basic than any other one. Hence either each process of a certain kind on each fundamental frame, including the ticking of clocks (such as the rotation of pulsars), occurs at a rate generally different from a process of the same kind on another fundamental frame, while on each frame a process of one kind occurs at the same rate relative to each process of another kind, or each process of the same kind occurs at the same rate on each fundamental frame. For example, either on every frame the natural frequency of a certain line of a caesium atom has the same value relative to the radiation frequencies of all other lines of atomic spectra on that frame but different from the frequency of that line on other fundamental frames, or the frequency is the same on all fundamental frames.

Clearly the simplest supposition to make and hence the one which is most probable in the absence of counter-reasons is the latter. This principle I shall call the Principle of Similar Clocks. If there are no objections to adopting the principle, then there will be a unique method of ascertaining the instant by the clocks on any galaxy at which a distant event occurred. For by the principle of isotropy either the mutual recession of galaxies has been going on since an instant by the clocks of our galaxy when all galaxies were very close together (an instant soon after the Big Bang) or it has been going on since an instant by the clocks of our galaxy when all galaxies were approximately stationary relative to each other. But in either of these cases clocks on each galaxy could have been synchronised at the instants referred to. In the first case clocks would have been very close together and so could have synchronised directly by comparison at what would be approximately the same place. In the second case, when all galaxies were approximately stationary relative to each other, all fundamenatal frames would have formed the same one most basic frame and hence there would have been a preferred frame. Clocks could then have been synchronized on this preferred frame by either method of indirect synchronization, making the simplest supposition about the applicability of that method compatible with the rest of physics. The simplest supposition (to be adopted in the absence of counter-reasons) about the velocity of light on it (even though it would not have been an inertial frame) is, as on any one inertial frame, that it has the same velocity in both directions. And the simplest supposition about the effect of motion on clock transport on this frame is, as on any one inertial frame, that the effect is non-existent for infinitely slow transport; and again in the absence of counter-reasons we should make this supposition. Since there are no such counter-reasons we should suppose that if these two tests had been done when the fundamental frames were close or stationary relative to each other, they would have yielded a unique simplest result – a fundamental observer on any frame would identify the same set of instants on all frames as simultaneous with each other. Hence there is a unique instant, a unique plane of simultaneity, by all the clocks on all frames at which the expansion of the universe began.

Given the principle of similar clocks, an observer on each galaxy can retrodict how many years ago by his clocks this early instant occurred; and his present instant will be simultaneous (absolutely) with the instant on the clock of each other galaxy when an observer on that galaxy judges that the same number of years have elapsed since that early instant. Every true clock kept stationary in its fundamental frame (that is, moved with the mean velocity of the matter in its vicinity) will have ticked at the same rate (relative to the true clocks on all other galaxies).

The Principle of Similar Clocks does not hold in the Universe of Special Relativity. There the equibasic frames are the inertial frames. Now consider three inertial frames A, B and C all moving with uniform rectilinear velocity relative to each other. At the initial instant of the experiment B passes A, and observers on each synchronise clocks directly; later B passes C which is moving towards A, and observers on C synchronize their clock directly with the clock on B. It is a consequence of the Special Theory that when C passes A the clock on C will record a smaller passage of time than the clock on A. For although processes of the same kind occur at the same rate on all three frames as measured by local clocks, processes on B and/or C occur more slowly than processes on A as measured by clocks on A. Consequently the Principle of Similar Clocks is false for a world of inertial frames. But in the actual universe, described by modern cosmology, the equibasic frames are not inertial frames, but galaxies (or more precisely the fundamental frames as defined earlier), and the possible relative motions of these are very different from the possible relative motions of equibasic frames on Special Theory. For the only instants, according to modern cosmology, at which a fundamental frame meets another fundamental frame are, because of the principle of isotropy, the instants, if any, at which it meets all fundamental frames. Hence an experiment of the type described above could not be performed for A, B, and C as fundamental frames. But if the universe were to contract and all galaxies come close to each other again, it follows from the Principle of Similar Clocks that a true clock on each galaxy whose reading could then be discovered directly or by light signal or clock transport methods by an observer on some other galaxy would be found to measure the same passage of time since the beginning of the expansion.

There could be evidence of a kind more readily obtainable about the truth or falsity of the Principle of Similar Clocks if messages were received (by light signal) from inhabitants of distant galaxies. They could report that at the instant of the sending of the message more years had elapsed since the instant of the Big Bang (or the instant at which all galaxies were stationary relative to each other) than we judge by our clocks at the instant of receiving the message. This would falsify the principle. Or such a message could report that less years had elapsed that we judge, and this would be consistent with the principle, since light would have taken some time to reach us.

The Principle of Similar Clocks gives us a cosmic time, a unique true clock for measuring the time of occurrence of events on the cosmic scale (e.g. the instant at which galaxies are a certain distance apart). It is clearly simpler to make measurements on a local scale by the same method as we should use on a cosmic scale, that is by clocks stationary in their fundamental frame. And there is an additional reason for regarding the local fundamental frame as the one true frame of measurement in which clocks should be stationary when they are used to make judgments of local simultaneity. This is that it is a consequence of our three principles (isotropy, equivalent laws, and similar clocks) and the assumption that light has its one-way velocity (c) relative to each fundamental frame through which it passes, that the universe is homogeneous and its geometry is everywhere uniform, and so that a formula known as the Robertson-Walker line element will hold. This asserts that [12] for any fundamental frame taken as origin an interval ds^2 is invariant:

$$ds^2 = c^2 dt^2 - R^2(t)\left\{\frac{du^2}{l - ku^2} + u^2 d\theta^2 + u^2 sw^2\theta\, d\vartheta^2\right\}$$

ds is the spatio-temporal interval between two neighbouring events E_1 and E_2. ds = 0 when these events are points on the path of a ray of light. E_1 occurs on a fundamental frame located by spherical polar coordinates (u, 2, ø) at cosmic instant t, and E_2 occurs at (u + du, 2 + d2, ø + d ø) at cosmic instant t + dt. 2 and ø are the normal angular coordinates. u is a 'co-moving' radial coordinate, such that if a frame has it at one instant it has it at all instants. It is related to the frame's 'coordinate distance' r by u = r/R(t). R (t) is a function of time, known as the scale factor of the Universe, and measures the extent to which frames are spread out. $R^{/}$ (t) is the rate of change of R(t). The greater $R^{/}(t)$, the greater (for given R(t))is the velocity with which galaxies are receding from each other. k is a constant having values k = 0 for Euclidean Space, k = + 1 for elliptic space (and also for spherical space). k = -1 for hyperbolic space. From the Robertson-Walker metric cosmologists develop various more specific 'models', that is cosmological theories, by giving a particular value to k and making some particular supposition about the equation governing the value of R(t).

The Robertson-Walker metric has the consequence that the one-way velocity of light on distant galaxies is not the same relative to all fundamental observers at all instants. The proper distance from a galaxy G_a at the origin, of a photon, the particle of light, emitted from a galaxy G_b having u-coordinate u_b at cosmic instant t_1 in the direction of $G_{a,,}$is at cosmic instant t_2:

$$l = R(t_2)\{\sigma(v_b) - \int_{t^1}^{t^2} . \frac{cdt}{R(t)}\}$$

where

$$\sigma = (u_i) = \int_0^{u_i} . \frac{du}{\sqrt{1-kv^2}}$$

Hence the velocity of the photon at t relative to G_a, marking velocity of approach by a negative sign, will be

$$\frac{dl}{dt} = R'(t_2)\{\sigma(v_b) - \int_{t^1}^{t^2} . \frac{cdt}{R(t)} - c\}$$

So, given an expanding (or contracting) universe (that is, $R^{/}$(t) □ 0), the (one-way) velocity of light passing through a distant galaxy must be judged by each observer to vary with his distance from that galaxy. Of course a distant observer cannot measure that velocity at that instant, but he needs to make a hypothesis about what that velocity is in order to explain the subsequent behaviour of the photon (e.g. when it will reach him) and the hypothesis which will most simply explain that behaviour is given by the above formula. One consequence of that formula is that, with a rapid rate of expansion of the universe, photons omitted from some distant galaxies will never reach us. (Such galaxies are said to lie beyond our 'event horizon'). Yet such galaxies are a finite distance away for us, and so if light had the same one-way velocity on such a galaxy relative to our galaxy as it does on our galaxy, any such photon would reach us at some later time. The situation in the actual universe as described by modern cosmology is quite different from that in the universe of Special Relativity.

As we saw in Section III, the local laws of physics acquire their simplest form if we suppose that the velocity of light locally is the same in all directions relative to the local frame. But that, we have now seen, has the consequence that it will not be the same in all directions relative to any other fundamental frame. I conclude that cosmic time provides a unique simplest and so probably correct standard of simultaneity not merely on the cosmic scale , but also on the local scale (by selecting a unique frame of reference, that of the fundamental frame associated with the local galaxy, relative to which local measurements should be made).

NOTES

1. This paper is a new version of material originally published as Chapter 11 of my Space and Time, second edition, The Macmillan Press, 1981. I am most grateful to Dr Pedro Ferreira for reading an earlier version of this paper and helping me to correct it in the light of the most recent cosmologicaldevelopments.

2. A. Einstein, 'On the Electrodynamics of Moving Bodies' (1905), in (tr) W. Bennett and G.B. Jeffrey, The Principle of Relativity, Methuen, 1923,pp 42-3.

3. See my Epistemic Justification, Clarendon Press, 2001, ch. 4.

4. There are prospects for replacing the caesium scale by a different scale also based on radiation frequency, an optical frequency of a line of either mercury or strontium, which being much greater than the caesium frequency would allow for more precise measurements of temporal interval. See <u>Science</u>, 19 November, 2004. This new scale would be merely a more precise form of the previous scale; it would not yield measurements different from those of the old scale, merely ones more precise. However it may well become established that the value of the fine structure constant (a) ,and so the radiation spectra of elements , are changing with time. (See for example J.D.Barrow, The Constants of Nature, Vintage, 2003,chapter 12.) In that case physicists would need to introduce a time scale based on fundamental laws in which that constant does not appear but from which it follows how that constant changes with time.

5. E.A. Milne, Kinematic Relativity (Clarendon Press, 1948), passim and especially pp. 244f.

6. I am not claiming that in all cases nothing could be ø when the best (logically possible) tests show that it is not ø, or conversely; merely that for any given ø, there is some reason for supposing that whether or not something is ø is whatever is shown by the best logically possible tests. I suggest however that reflection on the concept of 'equal temporal interval' suggests that necessarily two temporal intervals are of equal length if the best (logically possible) primary tests indicate that they are of equal length.

7. I. Newton, Principia, Scholium to Definition viii.

8. For examples of such conventionalism, see Hans Reichenbach, The Philosophy of Space and Time (originally published 1928) (trans. M. Reichenbach and J. Freund), Dover Publications, 1958, p. 117, 'All definitions … [of temporal interval] … are equally admissible'; and Rudolf Carnap, Philosophical Foundations of Physics, Basic Books 1966, p.83. 'We cannot say that the pendulum is the "right" choice as the basis for our time unit and my pulse beat the "wrong" choice.'

9. See Brian Ellis and Peter Bowman, 'Conventionality in Distant Simultaneity', Philosophy of Science 34 (1967), 116-36. This paper led to a panel discussion Adolf Grünbaum, Wesley C. Salmon, Bas C. van Fraassen and Allen I. Janis. 'A Panel Discussion of Simultaneity by Slow Clock – Transport in the Special and General Theories of Relativity' Philosophy of Science, 36 (1969), 1-81; to which Brian Ellis replied in 'On Conventionality and Simultaneity', Australasian Journal of Philosophy, 49 (1971), 177-203.

10. For the first stages of such a reinterpretation and demonstration of its consistency see Adolf Grünbaum, Philosophical Problems of Space and Time, Routledge and Kegan Paul,1964, Ch. 12, Section B.

11. Elie Zahar, 'Absoluteness and Conspiracy' in (ed.) Richard Swinburne, Space, Time and Causality, D. Reidel, 1983.

12. The mathematical results which follow are due largely to Rindler. See W. Rindler, 'Visual Horizons in World Models', Monthly Notes of the Royal Astronomical Society 116 (1956), 662-77.