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The Origin and Nature of Time

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I want to talk about some aspects of three issues about time, which we shall find are deeply related to one another : first, the contention that time and its partner, space, are « nothing » or « nothingness », or at least, if they do have some sort of existence, they are wholly indifferent to the matter, forces, and fields existing in the universe, neither influencing nor being influenced by those contents ; second, that space and time are necessary presuppositions of any physical theory ; and third, the question of whether time had an origin. These three issues are among the many which have concerned philosophers over the centuries. My interest here will be in what present-day physics, or the physics of the foreseeable future, can tell us about these questions. But along the way, I will make some comments about the roots of philosophical doctrines, and toward the end will draw some lessons about the relations between philosophy of science and science, and about how philosophy of science ought to be done.

I

Let us begin with the concept of space and time as nothing, or nothingness.[1] The doctrine of space and time as nothing is found in the ancient Greek atomists' identification of space with « Non-Being » (thereby bequeathing to later thought the paradoxes involved in the claim that nothing or nothingness exists). This view was also applied to time, through the common doctrine, first discussed by Aristotle, that neither the past nor the future exists, the past having once existed and the future not yet having come into existence. For a long tradition, this led to debate as to whether even the Now exists, it being a mere dimensionless instant : the only things that exist, many held, are the particular things existing at the Now, there being no additional existent, the transient Now itself.[2]

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[1] Any differences between the concepts of « nothing » and « nothingness » will be irrelevant here.

[2] [Sorabji 1983]. He writes about the early history of the concept of time, and in particular about the reasoning involved in considering time to be « unreal ». Histories of the concept of space are given by Jammer [1969] and, through the seventeenth century, by Grant [1981]. For the atomists' equation of the void with Non-Being, and the reasoning which prompted it, see [Kirk / Raven / Schofield 1985], who succinctly present the paradox involved : « Void,

The problem of the transience of the Now was one ultimate source of the « relational » view of space and time, according to which space and time are not entities, but only relations between physical entities and thus presuppose the existence of such entities. The major opposing view of space and time, that they do have an existence independent of their material contents, was held by Newton.[3] But even Newton held something in common with his opponents, for according to him also, space and time neither influence nor are influenced by their contents in any way. Except for their status as the arenas in which things exist and interact, they served as mere passive background, no more participants in the affairs of the world than the space and time which were by others considered to be mere nothingness. Although physical processes occur *in* them, space and time did nothing, were affected by nothing, and according to Newton's opponents were indeed nothing.

The doctrine common to both Newton and his opponents was thus that of the physical irrelevance of space and time : while things happen with respect to their spatial and temporal background positions, these latter neither influence nor are influenced by those happenings or their participants. Space and time are at most no more than mere passive background, in which physical processes occur, but which are irrelevant to those processes. Hence this doctrine was independent of the issue of whether space and time are to be interpreted as relative to choice of reference-frame or as the absolute framework with respect to which real positions and motions are determined. It was a common assumption of both sides of the dispute

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although it is identified as what is not, is accorded existence. It is hard to see how the atomists justified this paradox. » (page 415) The transformation of the concrete, practical, « oral » modes of expression found in the early Greek poets to the abstract, technical, « literal » vocabulary of the Presocratic (and later) philosophers, see [Havelock 1983], and for a more general account of the phenomenon, [Ong 1982]. [Meyerson 1962] examines relations between the concepts of space, time and « nothing. » An interesting discussion of the relations between the concepts of « vacuum » and « nothingness, » both in history and contemporary field theories, is found in [Weingard 1991]. Smolin's work, *e.g.* his [1991] and other works, also illuminate the roles of time in scientific explanation.

[3] Relational and absolute theories of space and time are examined in many places, *e.g.*, [Capek 1961], [Whitrow 1980], and, on a more technical but thorough level, [Sklar 1974], [Friedman 1983] and [Earman 1989].

between relationalists and absolutists. Furthermore, it was this more general view, and not the issues of relational versus absolute space and time, that was reflected in classical mechanics, electromagnetic theory, and quantum mechanics and its field-theoretic successors. For in those areas of physics, space and time have no role to play, except as passive, inert background of events taking place in them. Despite Newton, the question of whether this is because they have some philosophical reality or unreality proved largely irrelevant scientifically, at least until the end of the nineteenth century, and became the possession of philosophers. Yet the more general philosophical attitude was retained in science : whatever their « reality-status » might be, whether substance, accident, or, as Newton argued, neither, they are not the objects of study of physics ; they can be measured, and the results applied in various ways, including the formulation of scientific theories, but there was no theory *of* them themselves.

Leaving relativity aside for the moment, we find that classical physics, and even quantum theory, had precious little to say about the nature of space and time. There does seem to be one exception, at least with regard to the direction of time. For whereas the laws of other branches of physics are time-symmetric (considerations about neutral kaons aside), the second law of thermodynamics differentiates past and future states on the basis of their average entropies, their differences with regard to an average degree of order obtaining at different times. But this « law » is not like most other laws ; it makes no assumptions at all about the structure of matter or fields, and thus has no connections with those laws. Einstein called it a « theory of principle », as opposed to a « constructive theory. »[4] But its similarity to other « theories » lies in its being a general constraint on all explanatory (constructive) theories ; and so what Einstein's way of conceiving the distinction fails to bring out is that, in saying nothing about the deeper structure of things, the second law has more in common with purely factual statements than with fundamental theoretical explanations. And thus, whatever its other difficulties in defining an unambiguous direction of time,[5] it simply

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[4] For an illuminating discussion of Einstein's distinction, see [Klein 1967].

[5] The following selection gives an idea of the continuing discussion of the relations between thermodynamics and the direction of time : [Gold 1967] ; [Davies 1977] ; [Zeh 1989]. Some of the difficulties in the view that the

asserts the difference between past and future as a fact, without giving that deeper understanding that comes from connecting it with theories of detailed physical processes, and is not an exception to the claim that the theories I have mentioned gave no explanatory insight into the nature of time.

The idea that space and time have nothing to do with the events which go on in the universe, and that they are not objects of scientific study, was a powerful and pervasive one. Indeed, it seemed to many that those concepts had a special role in everyday experience and scientific theory. For Immanuel Kant, space and time are necessary preconditions of the very possibility of experience ; experience would be impossible without the mind being able to place the raw material of sensation in space and time. According to Niels Bohr and Werner Heisenberg, we must always rely on them (specifically, on the version of them that, according to those two writers, appears in classical physics and everyday language), and can never escape them.[6] The natural inference from such views (by no means confined to Kant and Bohr) was that space and time must be taken for granted, as fundamental, as the « background » in terms of which any physical theory must be formulated. As with the Greek atomists, the arguments for these positions are not relevant here : what is important for the present discussion is the fact that the conclusion, the irrelevance of space and time to physical processes, and, conversely, their status as preconditions of science or even of experience in general, was considered to be obvious and important enough to argue for in some way or other.

What could ever have led people to think of space and time as nothingness, or at least as wholly indifferent to what goes on in the universe, neither influencing nor being influenced by what goes on ? Why was it so widely accepted, even to the point where it was treated as so obvious as to be left tacit, and space and time left out of

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thermodynamic « arrow » clarifies the fundamental nature of time are discussed in [Sklar 1974], ch. IV, and [Sklar 1985], ch. X ; see also [Mehlberg 1980].

[6] « The Concepts of classical physics form the language by which we describe the arrangement of our experiments and state the results. We cannot and should not replace these concepts by any others. » [Heisenberg 1958], page 44.

scientific explanations, or, when made explicit, to be taken so often as a self-evident truth, an *a priori* condition of the very possibility of existence or experience ? Given our best present understanding of human beings and their history, evolutionary theory, there is no other way to view the source of such powerful ideas than in terms of adaptations to commonplace features of experience that affect us importantly as human beings. There are indeed commonplace features of everyday human experience that give rise to such an idea. We move easily, without resistance, through space, what resists our movement through space being due to the things in space, not space itself. The case is even more compelling for time, in which we slide without resistance from moment to moment. What forces us to move into the future are the things and events occurring, not time itself.[7] The most primitive minds at the beginning of human history (and before) must have become adapted to think, in dim and unexpressed ways, that the things they had to worry about, and worry about understanding, in the most primitive and rudimentary sense of that term, were the volcanoes, lions, food, rivals, potential mates, and offspring that occupied space and existed through time. And thus the idea that space and time are the mere background of experience, *in*

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[7] It might seem as though we cannot help moving through time, that we are like twigs floating in time, carried along irresistibly by its « flow » or « passage. » This view, too, has its ultimate roots in everyday human experience, even though in later philosophical developments it may contradict various versions of the « nothingness » view. There is nothing surprising in this : primitive, everyday experience can be shown to have given rise to many incompatible philosophical doctrines. However, despite its long history, and despite its mention by Newton, the idea of the « flow » of time has never attained scientific credentials, and in fact appears to be incompatible with the best-established twentieth-century scientific ideas about time. On the other hand, as the present paper argues, the « nothingness » view has been the basis for most physical theories in history, at least until general relativity. Specifically, the laws of physics specify how states *at* one time produce or affect those at a later time ; the transition from an earlier to a later state is not determined by time itself, the passage of time being determined only by transitions from state to state. From *this* perspective, which is a descendant of the everyday intuition of time as nothingness, we are not « carried along » from moment to moment by time itself, but rather by happenings in time. There is, of course, no problem about there having been a multiplicity of primitive sources of ideas, not necessarily consistent with one another when made explicit.

which what we have to worry about — to understand, in the most primitive and rudimentary sense of that word — takes place, but *about* which we do not need to be concerned, must have become deeply and unconsciously ingrained in human ways of interpreting the world. (One might say that the ancestors of present humans adapted to *not* thinking that space and time have causal efficacy.) This evolutionary account in terms of the commonplace reveals at once the source of the « necessity » with which some philosophers have endowed space and time, and also of the purely local, everyday character of those concepts. This way of interpreting the world around us found ultimate expression in the view that, in the attempt to understand the world, space and time are not objects of scientific explanation.

Modern science gives an insight into *why* it is that our everyday, local experience makes time and space seem to be nothingness, or at best to be irrelevant background of events which do have causal efficacy, and also of why this way of thinking is ultimately very limited and constricting once we begin to investigate the universe well beyond everyday experience. General Relativity is a theory of space and time, but simultaneously it is a theory of gravitation, in which gravity is understood in terms of the curvature of space-time. But the connection between gravitation and space-time remained unsuspected until General Relativity, and for good reason. For while gravity has a tremendous effect in everyday life, it is such a weak force that no association of it with space and time is noticeable on our human scale of experience. Gravity makes itself known only where a large amount of matter, like the earth, is present, and so it is natural to attribute it to the fact that we are on earth, or at worst (for Aristotelians) because we and the earth are located in a particular place in the universe. No one would have had any reason to think that space and time (much less space-time) were the source of gravity through curvature (after all, the radius of curvature of space-time which accounts for the earth's gravity is measured in light-years) ; rather, gravity was to be related to matter (or, for Aristotle, to matter's static location) *rather than* to a dynamical effect of the curvature of space-time. It is the overwhelming presence of matter when gravity is present that impresses us, and that, historically, proved decisive in our attempts to construct explanations of it. By this path of thinking, the belief that space and time do not have any physical effects remained viable, and even shaped the character of explanations of gravity. And so we see why space in particular, and by extension time, could be thought of by so many, beginning with the Presocratic atomists and the Aristotelians and continuing well into modern times, as « nothing », and how that idea flowed so easily into the view that, while things exist and events take place with respect to space and time, those latter two concepts are not themselves objects of physical study and explanation. A similar explanation holds for why Newton thought that time « flows equably, without relation to anything external », and that space « in its own nature, without relation to anything external, remains always similar and immovable », neither being influenced by the « external » material content nor influencing it.[8] It would eventually turn out, however, that while this lack of physical effect is an extremely good approximation on the local level of everyday experience, it is not on other scales.

If our concepts of time and space originated from the characteristics of local, everyday experience, then how have we managed to get beyond those everyday concepts and their modern descendants ? For relativity theory *has* gotten beyond them, at least to a certain extent. Special Relativity compelled us to fuse the concepts of space and time into a unified space-time, with separate simultaneity and length measurements being relative to choice of inertial reference-frame. General Relativity, through its identification of the metric field with gravitation, attributed to space-time (*i.e.*, the manifold plus the metric) a dynamical role. Unlike the theories mentioned above, it is a theory of space-time as physically interactive with the matter - and energy - content of the universe — as Einstein said, as a participant in, and not merely as an independent

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[8] Sometimes Einstein put a post-Riemannian gloss on Newton's view of the relation between inertia and space, as in his introduction to [Jammer 1954] : « The concept of space was enriched and complicated by Galileo and Newton, in that space must be introduced as the independent cause of the inertial behavior of bodies if one wishes to give the classical principle of inertia (and therewith the classical law of motion) an exact meaning. » [Jammer 1954], xxiii-xiv. Whether or not the Riemannian « guidance » of inertial motion along geodesics is necessary to give the Newtonian concepts « an exact meaning, » Newton himself would never have thought of the matter in this way, nor could anyone until after Riemann.

background arena for, the events taking place in the universe. In this paper I will not deal with the question of how we have been able to go beyond our local evolutionary heritage, restricting myself to reminding you *that* we have done so.

The understanding of time gained from General Relativity is limited in fundamental ways. General Relativity breaks down at very high energies, or, equivalently, short distances or times. Despite earlier suggestions, it is now known that the existence of singularities is not simply an artifact of the way the mathematics of the theory was done ; the singularities cannot be avoided.[9] Hence General Relativity is not a theory of space-time at the most fundamental level.

Another, deeper way of seeing the limits of our understanding of time is to recall that we have no unified understanding of the relationships between, on the one hand, our best theory of matter and non-gravitational forces, the Standard Model of elementary particles and forces, and, on the other hand, our best theory of gravitation, General Relativity. But since General Relativity is also a theory of space-time, it follows that what we lack is a unified understanding of the relations between matter and non-gravitational forces on the one hand, and space-time on the other. More specifically, we have no understanding of the relationships between our quantum theories of the elementary particles and the forces between them — the universe in the very small, that is, at short-distance and high-energy scales — and the theory of the universe on the large scale. As we will see shortly, this lack of understanding is reflected in the fact that, even in quantum field-theoretic calculations of quantum processes, space-time functions in the same old background role.

II

The directions in which physics has proceeded in recent years give promise of providing such a unified understanding of space,

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[9] The argument that the singularities were artifacts of the way we were dealing with the problem mathematically, and that they would be avoided in reality, was argued by Lifshitz / Khalatnikov [1963]. That this was a vain hope, and that the singularities were necessary features of General Relativity, was shown in a series of papers by Hawking and Penrose in the 1970's ; see, *e.g.*, [Hawking / Penrose 1970].

time, matter, and force, and illuminating the question of the origin and nature of space-time, and especially of those special characteristics which we associate with time. A brief survey of some of those directions will bring out a few of the ways in which the nature of time (and space) might be illuminated in such a unified understanding, and also the respects in which the thinking about the possibility of such illumination is well-founded as opposed to being mere speculation.

The Standard Model of elementary particles and forces, developed over the past quarter century, is a juxtaposition of the gauge theories of the electroweak force, a partial unification of the electromagnetic and weak interactions, with the gauge theory of the strong force, quantum chromodynamics. It is not really a unified theory — that would be the job of a so-called « GUT » (« grand unified theory » of the strong and electroweak forces — but not including gravity). But it is an enormously successful one, both because of the special characteristics of its mathematical structure, that of a gauge theory, and because of its consistency with all empirical evidence from the very smallest accessible scales to the very largest, so that many recent major conferences on the subject have amounted to a celebration of the success of the Standard Model and its components.[10] It is the application of this theory to cosmology, and the attempts to incorporate the fourth fundamental force of nature, gravitation, into a still more powerful unifying theory beyond the Standard Model and GUTs, that constitutes the first of two approaches to a deeper understanding of nature, and in particular of the origin and nature of time, that I will consider in what follows.

The application of the Standard Model to cosmology was a natural one. The Standard Model declared that the unification of the electromagnetic and weak forces would be realized in nature at an energy of roughly 10^2 GeV, corresponding to a temperature of 10^{18} °K, while a GUT unification of this electroweak force with the strong

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[10] *E.g.*, [Drell / Rubin 1994]. In their papers at this conference, Frank Wilczek could state flatly that « QCD is right, and we can do many beautiful things with it, » and David Gross asserted that « The main message from this meeting, as well as all other meetings in the last few years, is that the standard model — the electroweak theory and QCD — works extremely well. »

would occur at roughly 10^{15} GeV, or a temperature of 10^{27} °K. Where (or when) would such high energies actually be realized in the universe ? The answer was ready in the increasingly well-confirmed « Hot Big Bang theory » : in the very hot (*i.e.*, very high energy) young universe. As the universe expanded and cooled, the symmetries — the unity — of the forces would be successively broken, that of the GUT unity at about 10^{-35} seconds after the Big Bang, the electroweak unity at 10^{-10} seconds. The new gauge theories made possible calculations of processes occurring at these very early times (chiefly, they made application of perturbation theory possible).[11]

Only the fourth fundamental force, of gravitation, still lay beyond the purview of unification. But the programme of particle physics as to how to work it in — the directive as to how research into further unification ought to proceed — seemed clear, dictated by the enormous success of the Standard Model. The fourth force would be unified with the other three at a still higher energy, 10^{19} GeV, prevailing at a still earlier time in the history of the universe, the Planck time, 10^{-43} seconds after the Big Bang. The way to achieve a theory of what went on at that full unification stage was to use the tried-and-true methods of the « gauge-theoretic revolution » : find a further gauge group which would include the gauge groups of the theories to be unified as subgroups, and which would permit the application of perturbation methods to the solution of dynamical problems.

In line with this directive, the predominant approach of the particle physicist to unification, given the great prior success of the approach, has been to treat gravity as just another quantum field whose gauge particles, the gravitons, interact according to Einstein's field equations.[12] The gravitational field (and its exchange particle,

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[11] It was shown that many non-Abelian gauge theory (those with negative β-function), such as quantum chromodynamics, imply « asymptotic freedom, » which means that with increasing energies, particles increasingly approximate freedom from the influences of other particles. Any interactions that do take place can therefore be treated as minor corrections (perturbations). [Gross / Wilczek 1973] ; [Politzer 1973].

[12] Accessible surveys of approaches to the development of a theory of quantum gravity, or more generally of a « theory of everything, » are given in [De Witt 1983] ; [Wald 1984], ch. 14 ; [Isham 1989] ; (Kolb / Turner 1990], ch. 11 ;

the graviton) can be shown to have spin 2, and to consist of ten component quantum fields — precisely the number of metric tensor components of a curved 4-dimensional space-time in classical General Relativity. Treatment of the space-time metric as a fluctuating quantum field thus inspires tantalizing hopes of a fully unified theory in which the gravitons would interact not only with each other, but also with the quanta of the other fundamental fields, those specified by the Standard Model and a higher GUT unification based on it.

Within this programme, several approaches are available. A particularly popular one which is especially relevant to the present discussion is called covariant perturbation theory. In it, one begins by distinguishing a background Minkowski flat metric, and considers curvature as small corrections to that background space. Thus it is typical weak-field perturbation-theory physics. More importantly for our purposes, it illustrates what I discussed earlier : it is yet another instance of taking the background space-time for granted, leaving it unexplained. Note that this is true also of present treatments of other problems. For example, even in « semi-classical » approximations where quantum effects are examined against the background of the space-time of General Relativity, the latter is simply the background, which is taken for granted.[13] In superstring theory, too, space-time still functions as a background in which string vibrations occur, a far

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[Ashtekar 1991] ; [Shapere 1991]. The flavor of much recent discussion can be found in [Gibbons / Hawking 1993] ; [Ashtekar / Stachel 1991] ; [Penrose / Isham 1986] ; [Hawking / Israel 1987]. Another important type of approach taken by many particle physicists has been the appeal to Kaluza-Klein theories [Applequist / Chodos / Freund 1987]. However, the various versions of this approach are more appropriately seen as emerging from the geometrical approaches advocated by workers in general relativity. Kaluza-Klein approaches attempt to view the universe as having emerged from a primordial state of higher dimensionality. They treat the forces and particles of the present-day universe as results of a compactification of certain of those dimensions (those having to do with particles and forces), the spatiotemporal dimensions remaining uncompactified. In an important alternative to this approach, [Brandenberger / Vafa 1989] have proposed that a *de*compactification of spatiotemporal dimensions from a primordial unity is a more natural approach to questions about the early evolution of the universe.

[13] See the discussion in [Kolb / Turner 1990], 448.

cry from the ambition of the theory, which is to have our 4-dimensional space-time emerge as a consequence of string dynamics.[14]

Treatment of curvature as a weak-field perturbation has been the source of much criticism. A host of alternative approaches to a unified theory, related primarily by the fact that their advocates come to the problem not from the perspective of particle physics but from General Relativity, look on such weak-field treatments as superficial. The latter, it is said, would commit us to a topology identical with that of Minkowski space, thus excluding at the outset many cosmologically-relevant solutions of Einstein's equations. The perturbation approach, it is argued, excludes strong-field possibilities which cannot be ignored in a quantum theory of gravity. Can fluctuations in space-time in the Planck era be from one topology to another — for example, from space dimension to time dimension? In number of dimensions (if the number of dimensions is even well-defined)? In connectivity? In other words, the possibility of large fluctuations, *e.g.*, from topology to topology, is ignored in a weak-field approximation. The argument is that these possibilities cannot be ignored, because topological fluctuations, if they occur, could determine the values of fundamental constants, for example the cosmological constant, the value of which poses considerable difficulty in present cosmological theories.[15] If such proposals come

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[14] There is no contradiction between the idea that strings have length and vibrate and the idea that space-time emerges from strings. In superstring theory, the string length is measured with respect to a 2-dimensional world sheet ; the world sheet metric and the space-time metric are treated as independent entities. Integration is performed over the string modes, the space-time metric arising simply from one of the vibrational modes of the string.

[15] See [Weinberg 1989] for a review. At first glance in this ongoing controversy, we seem to find features which we have seen so often in major developments in the past. There is a « standard programme », applying methods which proved successful in the past. And there is the position, viewing that programme as ignoring fundamental problems and possibilities. They accuse the standard approach of superficiality, to which adherents of the standard approach respond that we must not be wildly speculative, that we have to take one step at a time, building on the concrete empirical successes which have led to scientific progress. But though there is something to this history-repeating-itself picture, it is not entirely accurate ; there are deep

to be fully developed and accepted, the full brunt of topology, whose modern evolution was initiated almost exactly a century ago by Henri Poincaré,[16] will be felt at last in physics ; just as has already happened with the metric, topology will no longer constitute the mere indifferent background of physical events, but will acquire a fundamental role in the dynamics of nature.

In fact, however, neither of the two sorts of approaches I have considered has been particularly successful so far. While some of the particle physicists' attempts to construct a GUT were attractive, they had to wrestle with empirical results concerning proton decay ; apart from that and other problems, there were just too many appealing GUTs. Many physicists leapfrogged the GUT level when superstrings became fashionable ; but despite early promise, the number of conformal field theories obtaining the Standard Model from superstring theory runs at least in the millions.[17] And superstring theory has to date made no contact with experiment. With the

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differences between the present case and earlier ones in the history of science. Fully as much as the Standard Model, general relativity is also a highly successful theory ; it too has passed a good many severe empirical tests in recent years (all but one of which, however, is a weak-field test). And as for wild speculation, superstring theory, the most recent darling of unificationists, deals with entities and processes some seventeen orders of magnitude beyond our present experimental capabilities, and probably very far beyond what we will ever be able to achieve experimentally ; nor has it yet furnished any low-energy consequences subject to empirical test. The opponents of the standard approach are not wild-eyed revolutionaries intent on overthrowing the established scientific order ; *both* sets of approaches are, on the whole, well established scientifically ; and the opposing sides are — increasingly in recent years — prone to use each others' methods, and to communicate with each other and often to work both sides of the fence, unlike what would be expected of advocates of radically different approaches, or « paradigms. »

[16] See [Poincaré 1895]. This work was followed by a series of supplements in 1899, 1900, and 1904. Poincaré's work was in combinatorial (algebraic) topology rather than in point set topology, which plays a prominent role in these physical problems. However, Poincaré's contribution was to bring to the fore the independent unity of the discipline concerned with topological invariants (homeomorphisms), a search which spans both approaches to topology.

[17] [Kawai / Llewelyn / Tye 1987]. There are signs, however, that this may turn out not to be a serious problem. For a general survey of the present situation in particle physics, see [Shapere 1991].

resulting onset of disillusionment about the possibility of a quick unification of all fundamental forces and particles, the optimism of the early 1980's, the confident faith that the standard approaches of particle physics would triumph as they had in the past, was lost. No longer ignoring the charges of their general-relativistic critics that perturbation methods ignore crucially relevant strong-field possibilities, the particle physicists often counter with the more defensive claim that the problem of quantum gravity is too complicated to be approached head-on, that progress is to be achieved by beginning with the simple and only gradually including more and more of the complex as the latter become tractable. But whether it will indeed be possible to achieve success by beginning with the simplest tried-and-true approaches remains to be seen. Though historical induction is a poor guide to present research and future possibilities, one cannot help noting that in past historical instances, more radical approaches have frequently been the successful ones.

But the high ideal of the general relativistic opposition, to include even the most bizarre topological possibilities from the outset, has not been attained either. The accusation of superficiality, insofar as it means omitting important possibilities from calculations, applies also to their programme. For example, those who approach the problem of constructing a theory of quantum gravity with the idea of summing over the histories of all possible universes are unable to achieve such ideal thoroughness ; in practice, they deal only with « minisuperspace » which includes only a finite number of degrees of freedom of the superspace of universes. And on the other hand, what would a successful application of the theory involve ? Are we really to exclude *no* possible histories (*e.g.*, fluctuations in dimensionality) as irrelevant to our actual universe?

In short, we do not have the promised unification of the quantum and General Relativity realms. Nevertheless, more recently, both approaches appear to have recognized the criticisms leveled against them, and the line between the two sides has become blurred, and more unified approaches are being developed. Especially in the last few years, much about possible directions in which to go has become well-formulated, as are the problems in those directions. Many features of the expected unifying theory are believed known, at least in outline : though one can never be absolutely sure what the next acceptable theory will look like, in the present case there are signs which are strong enough to suggest reliability. Therefore it is possible to examine at least some broader outlines of what the various hoped-for unifying theories would do, specifically in regard to time. I will mention only those possibilities which are directly relevant to the three issues of this paper.

In particle physics, the way unification has been achieved so far has been through showing that group-theoretical transformations in the unifying theory remove the fundamental distinctions between entities and forces treated as distinct in the separate theories that are unified. Thus some GUTs (those with supersymmetry) postulate the interconvertibility of fermions and bosons, which are rough quantum-mechanical descendants of classical concepts of matter and force, respectively. In a still higher unification, this unified concept of matter-force would be fused with gravitation, that is, with space-time, the fusion of space and time. In some scenarios a symmetry breaking (or compactification or decompactification of a higher- or lower-dimensional space) would serve to bifurcate the primordial unity, and thus to provide an origin of space-time, and of space and time as we, in our cold world today, know them. By relating relativity to fundamental particles and forces, it would be, in Einstein's sense, the first fully constructive theory of space and time that we have ever had, fulfilling the hope that the laws of physics themselves might determine such things as time's arrow and give scientific answers to other problems philosophers have worried about, as well as exposing entirely new facets of time.[18]

Many radical proposals have been made by general relativists in the attempt to construct a theory of quantum gravity. Some of these I

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[18] Perhaps, too, light would be shed on the interpretation of quantum theory : after all, one aspect of non-locality is the continued entanglement of behavior of particles which are spacelike separated. Another intriguing possibility is that various asymmetries found in the universe today might turn out to have a unified explanation : the overwhelming predominance of matter over antimatter, the occurrence of asymmetries like parity and even perhaps molecular chirality, and the only case of temporal asymmetry found in particle physics, the decay of the neutral kaon, all involve the weak interaction. Is it possible that whatever it is in the unified theory that serves as a precursor of the weak interactions is responsible at once, ultimately, for all three phenomena, matter, chirality, and time ?

touched on earlier, ones having to do with topological fluctuations. But the most radical suggestion, at least at first glance, is that time (and space) have no significance in a fundamental theory of nature, but would arise from that fundamental theory[19] : that is, that space and time will no longer be mere « background » of physics, but will find their origin and nature explained scientifically. Yet such a suggestion is not as surprising as all that, since one result of a group theoretical unification in the particle-physics tradition would also be that time is a product of physical processes, rather than being something assumed at the outset. Despite its failure to achieve this aim so far, superstring theory has solutions in which space-time does not appear ; presumably a final unifying theory would show why such possibilities are not realized in the universe we live in. Thus, both particle physics and general relativity approaches, at least in some of their versions, hope to explain the origin of time through their ultimate unifying theories.

III

At the beginning of this paper, I raised three issues which I said would turn out to be deeply related to one another. I have now shown the roots in human history of the concept of space and time as nothingness, and how those primitive roots, together with the extreme weakness of the space-time aspect of the force of gravitation, contributed to the view that space and time are only the background of any physical theory, not to be explained by such theory ; and we have seen the rise of possibilities denying that exclusively background status, and unifying the dynamical function of space-time with quantum field theory to explain the origin and nature of time. This has been an account of how the concepts of time and space have begun to be removed from the exclusive context of common sense and philosophy, and, though quite belatedly, internalized into the scientific process of scrutiny and change from which they had been exempted before our century.[20] It has been a process wherein time and space no longer have the exalted status of

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[19] *E.g.*, [Horowitz 1991] and [Rovelli 1991].

[20] This process of internalization of the concept of time was only initiated with the theory of general relativity, and as is seen in this paper, has been carried much further in subsequent physics.

preconditions of all possible experience, or of the wholly neutral background of physical events, or, more extremely yet, of nothingness, but have become concepts *of* physics, like any other physical concepts subject to alteration and explanation, and whose interactions with other things in the universe are to be understood.

As we saw earlier, Kant held that our concepts of space and time are preconditions of all possible experience. Nevertheless, Kant also maintained that those concepts cannot be extended to the universe outside the normal range of human experience (the levels of the very large and the very small) without getting ourselves entangled in antinomies. Bohr agreed with at least the heart of both Kantian theses : while he held the classical concepts of space and time to be presuppositions of experience built into everyday language, from which we can never escape, he nevertheless maintained, like Kant, that we cannot expect that the universe on the scale of the very large and the very small will fit concepts which have been designed to deal with our « middle-sized » world of experience. In this common conclusion, Kant and Bohr were correct ; the concepts of space and time which we employ in the everyday world have proved inadequate for understanding the universe we live in, either on the level of the very small or the very large. They erred, however, in supposing that we can never get beyond those ordinary concepts and develop new concepts of space and time, rational descendants of those used on the everyday level and both consistent and empirically adequate to account for both the everyday realm of experience and the levels beyond it. As I remarked earlier, in this paper I have only pointed to the fact *that* such changes have come about ; here I have not been able to show *how* it has been possible to do so, largely through the powers of mathematics that can transcend the limits of human visual imagination and ordinary language ; nor have I here traced the reasoning by which those changes have come about.

Aside from these and other exclusions, this paper has been intended to exemplify an approach to the understanding of the scientific enterprise that has not been common among philosophers of science. We have, or should have by now, learned that we cannot dictate, from an armchair, how inquiry must proceed, and what its results must be like, or what nature must be like ; nor can we stand above science, determining, independently of any results of science, what the science-transcendent criteria are of what it is to be an observation, or the necessary conditions for being real.[21] It has turned out that there is more *to* heaven and earth, and in the potentialities of human thought, than is dreamt of in philosophy. In the light of that lesson, what we need to understand (whatever we call the subject that tries to get such understanding) is how those potentialities, and the knowledge-seeking enterprise which exploits them, are possible : firstly, how we human beings have been able to get from *there*, the most rudimentary and primitive mentality of the everyday, to *here*, the world of space-time and the quantum field, and how we have been able to conceive of new possibilities. Secondly, we want to ascertain the significance of that exploitation : what it is we have attained today — how much confidence we can place in our present ideas, as giving a reliable portrayal of our universe, to assess the strengths, weaknesses, and unvanquished rivals of that view, and what we can attain or justifiably expect or hope to attain in the future. And finally, we want to understand the place of human beings in the context of the scientific beliefs we have attained, may attain, or hope to attain. In the example of time explored here, we have had a brief glimpse of a small but historically important fragment of these issues. We have seen that when we internalize our everyday concepts into the scientific process, we often manage to alter them, sometimes conceiving possibilities radically different from what common sense, or philosophy either, has thought is and even must be the case ; and we sometimes even come to accept such possibilities.

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[21] For scientific departures from everyday and philosophical concepts of observation, see [Shapere 1982], and for similar departures with respect to the concept of reality or existence, [Shapere 1990].

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