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This article aims at elucidating the philosophical elements in two contemporary (post 1975) research programs in theoretical cosmology. The programs of R. Penrose and S. W. Hawking differ with respect to their view of the basic structures behind space and time, the interpretation of quantum physics, the arrow of time, and the specialness of our Universe. The differences show up both in the content of their work and in the arguments used to defend their programs. The present article shows that these differences are partly of a philosophical (mainly metaphysical) nature, probably the "dangerous but fascinating territory" mentioned by Penrose. As far as this conclusion is justified, it supports the general conjecture that fundamental research programs do have some metaphysical component, although that is often not explicit. They might be seen as examples of theories which are "logically incompatible and empirically equivalent" and hence examples which might have some relevance to discussions about the tension between "realism" and "underdetermination". A comparison of two different programs makes it easier to see some of the implicit or explicit decisions involved.

1. Introduction.

The emergence of quantum physics and general relativity was accompanied by an intense philosophical debate about the implications for Kantian and positivistic philosophy, as exemplified for instance by the volume on Einstein in the Library of Living Philosophers ([Schilpp] 1949). As I hope to show in this article, the issues at stake in contemporary ideas beyond quantum theory and general relativity are at least as important. However, they have not led to as wide a discussion. The absence of interest can partly be explained by the difficult mathematics involved and the enormous volume of scientific production today. The ideas lend themselves less easily to popularization, although that surely will come if the ideas are here to stay. Another reason for the relative scarcity of attention might be that the programs are still unfinished.

This article aims at elucidating the philosophical elements in two contemporary (post 1975) research programs in theoretical cosmology. The programs of Penrose and Hawking[1] differ with respect to their view of the basic structures behind space and time, the interpretation of quantum physics, the arrow of time, and the specialness of our Universe. The differences show up both in the content of their work and in the arguments used to defend their programs. The present article shows that these differences are partly of philosophical (mainly metaphysical) nature, probably the "dangerous but fascinating territory" mentioned by Penrose. As far as this conclusion is justified, it supports the general conjecture that fundamental research programs do have some metaphysical component, although that is often not explicit.

They might be seen as examples of theories which are "logically incompatible and empirically equivalent" (Quine [1970]), and hence examples which might have some relevance to discussions about the tension between "realism" and "underdetermination". A comparison of two different programs makes it easier to see some of the imlicit or explicit decisions involved. However, they each have their own formalism, use their own language, and that obscures direct comparison, since apparent differences might be due to presentation. It would be better to reformulate the theories as far as possible in a common scheme, as M.Friedman [1983] has done for Newtonian and Einsteinian theories of space and time. However, it would not be feasible to reformulate the ideas of Hawking and Penrose at this moment. Besides, we are dealing more with "work in progress" than with a finished product. A further justification is that they address the same scientific audience at conferences.

In relying on their own statements there is another difficulty: a scientist need not be the best interpreter of his own theory. However, as their proposals are rather complicated I follow the interpretations given by the authors. Besides, although upon closer analysis the actual content of the resulting theories might have different conceptual implications than those claimed by their proposers, the statements made by the proposers remain the most direct source about the ideas involved in the development of the theories. Hence the article gives my reconstruction of some methodological and metaphisical ideas implicit in the work of Hawking and Penrose.

Penrose's approach is sketched in its development from the early 1970s, concentrating on twistors instead of space-time points (3.1) and on the arrow of time, the initial conditions of the universe and the interpretation of quantum

mechanics (3.2). Then follows a discussion of Hawking's recent work (since 1982) in quantum cosmology (4.1), and its implications for his view of time and quantum reality, and his expectation that physics might be near completion (4.2). Background information on physics is given in a preceding section (2). In the final section (5) the scientific work is presented in the terminology of Imre Lakatos" methodology of research programs. It is claimed that the metaphysical component of these research programs can best be thought of as residing in the "positive heuristic". The metaphysical elements are also claimed to be much more like traditional mataphysics than is acknowledged by Lakatos description of them as contingent propositions without potential falsifiers.

2. Background Information on Physics.

In theoretical physics the major fundamental theories are general relativity (GR), quantum theory (QT), and thermodynamics.

Applying general relativity to the universe as a whole, space-time has a boundary point where the curvature becomes infinite, the so-called big bang. Other singularities arise in the collapse of a heavy star. Singularities are unavoidable in GR, provided certain general assumptions (Hawking and Penrose [1970]) are fulfilled. Singularities are naked or, as black holes, have horizons. In the latter case, everything inside remains trapped forever, so the core singularity does not influence the external universe. As the basic equations are time-symmetric, white holes - emitting singularities - are also thinkable.

Quantum theory describes systems by a wave function, or equivalently a state vector, which gives probabilities of

events. The probabilities are squares of comlex amplitudes. (One complex number is equivalent to two real numbers). Spin is a characteristic of particles which comes in units of 1/2 . A system with helicity 1 (one unit of spin) can be in a state which mixes spin "up" and spin "down", described by two amplitudes. Penrose refers to this "plane" of complex numbers as a complex continuum, in this case C_2. As there are vectors in space-time, there can be defined in C_2 a kind of complex vector, a "two-spinor".

The interpretation of QT is still controversial. The Kopenhagen Interpretation is that the collapse to one actually observed result is a real effect, induced by the act of observation (by instruments). Others hold that all possibilities described by the wave function are equally actual, the Many Worlds Interpretation. There are more subtleties as well as modifications of philosophical interest, but this suffices as background.

Thermodynamics is the only fundamental theory which makes a physical difference between past and future, and so has an "arrow of time". Dissipatory phenomena are summarized in the Second Law: a mathematical entity called "entropy" increases until equilibrium is achieved.

Although the theories work very well in their respective domains, a combination is needed both for aesthetic reasons and for application to certain interesting situations, such as the very early universe and black hole thermodynamics. In the case of black holes there is a close analogue of the Second Law in that classically the surface of the horizon always increases. Hawking [1975] discovered that a black hole might produce radiation by quantum effects, now called Hawking radiation, and thereby evaporate completely.

3. R. Penrose's Twistor and Time Program.

3.1. The Twistor Program.

Although the program originated earlier[2] an article published in 1972 is taken as a clear statement about the program in an early stage.
"On the Nature of Quantum Geometry" [1972].

Penrose objects to the mathematical continuum since it contains "many features which are really very foreign to physics" ([1972], p.333). A small volume would contain as many points as a large volume, or even as the entire universe, which is unrealistic. There is "the lack of firm foundation for assigning any physical reality to the conventional continuum concept" ([1972], p.334). According to Penrose the continuum problem is as strong for quantum theory. His long term policy is "that ultimately physical laws should find their most natural expression in terms of essentially combinatorial principles, that is to say, in terms of finite processes such as counting or other basically manipulative procedures" ([1972], p.334). Penrose does not envisage a discrete set of points, but he expects that "the concept of a space-time composed of points should cease to be an appropriate one - except in some kind of limiting sense" ([1972], p.334). As this also holds for the other continuum, "quantum theory and space-time theory would be expected to arise together, out of some more primitive combinatorial theory" ([1972], p.335). As motivation Penrose mentioned also "the infinite divergences of quantum field theory" (Penrose and MacCallum [1973], 243).

A first prototype: spin networks.

Penrose then describes a model with angular momentum as the basic entity. It is discrete. The "world" in this model are line segments with spin. To nmeglect quantum uncertainty for a system with sufficiently large angular momentum one can define a direction by means of its rotation-axis. Once directions are defined, angles can also be defined. "Thus, the system itself defines the geometry and the background space is really an irrelevance" ([1972], p.339). If a system consists of two parts, each defining directions and angles, it is possible that the two geometries do not fit together the way an Euclidean background does. This might represent curvature of space-time.

In an argument not directly related to spin-networks but essential to the spinor and twistor approach, he introduces a six-dimensional "space" where each point represents a whole line (geodesic) of the original space-time. The geometry of ordinary space-time can be reconstructed out of this space of points representing lines. Normally, a point is the intersection of a bundle of lines. However, if there are different patches of flat geometry, points in one region will appear "fuzzed out" if the geometrical structure of another region is used. This can be imagined as the bundle of lines no longer intersecting at one point, due to the shear acting on the geodesics.

Penrose explicitly points to unrealistic aspects of the spin-network model ([1972], pp.338 & 347). Most important, it is non-relativistic and the mixture of spin and orbital angular momentum is not treated adequately. Both problems are related to the neglect of the relative velocities by paying attention only to angular momentum.

Twistor theory as the next step.

Penrose advances a number of reasons why twistor

theory might provide a better framework. In using twistors he specializes to null geodesics: world lines of light and other massless particles. This is justified by the following arguments: (1) The space of points representing lines (a) attains a nice mathematical structure in this approach and (b) shows a similarity to modern theories of elementary particles. (2) Null geodesics are conformally invariant, that is invariant under all angle-preserving transformations like rotations, translations and scale-transformations. Conformal transformations preserve the causal structure of space-time. Rest mass conflicts with invariance under scale transformations. "In any case, to think of basic physical processes in terms of either conformal invariance, or the breaking of conformal invariance, seems to be a fruitful point of view. To this end, it is very useful to employ a formalism which makes this conformal invariance manifest wherever it is present" ([1972], p.347). (3) It is a generalization of the spin-networks with conformal invariance in stead of rotational invariance. Therefore we might be able to derive a similar combinatorial calculus. (4) It overcomes the difficulties mentioned above in that twistors are fully specially relativistic and mix spin and orbital angular momentum in the right way.

Penrose suggests reconciling conformal invariance of flat space with GR along the lines described above: the idea that local patches do not fit together in a flat way, corresponds to fuzziness (incorporating QT) and curvature (incorporating GR). "To a considerable extent, the above program is speculation. Nevertheless, the present state of twistor theory does have a number of points of contact with it" ([1972], p.348), as he illustrates in the remainder of that article.

Later articles.

The same motives are repeated. The primary aim is the merging of the two continua (space-time and quantum probabilities) into one, which would explain the 3-1 dimensionality of space-time. A longer term aim is to eliminate the continuum concept in favor of combinatorial principles. Twistor theory clearly follows up the first aim, but Penrose acknowledges that it is unclear whether this, even if successful, would provide the reduction of physical laws to combinatorial rules ([1975], p.273). As far as I know of, the first time that the interpretation of quantum mechanics is mentioned is in ([1980], p.288), where it is mentioned together with the infinities in quantum theories.

The equivalence of the twistor description in terms of points representing lines and the classical description is conceded, but they provide radically different views of quantized space-time. Usually the points are kept intact and the metrical structure is quantized, which makes nullcones (and causality) fuzzy. Penrose wants to keep the null directions well defined (the twistor space of points representing such lines). Instead, he allows for fuzzy points as intersections of such lines. "A viewpoint of this kind also fits in well with a belief (which is itself part of the twistor philosophy) that spinors are to be regarded as more fundamental than world-vectors" ([1975], p.275). That twistor theory works with comlex numbers hints at a unification of space-time and quantum physics. "Such unifications and hints at unifications that the twistor approach provides are, to me, a stronger motivation than any of the more clear-cut achievements of the theory" ([1975], p.277). Besides, the formal equivalence at the classical level does not imply that the twistor approach might not be more useful in certain calculations ([1975], p.304).

Twistors are introduced physically as objects consisting of two spinors (each consisting of two complex numbers) representing the momentum and angular momentum of a massless particle of a certain helicity. Such objects are shown to satisfy a certain equation, the twistor equation. Subsequently, this is turned upside down: twistors are defined mathematically as the solutions of this equation. Penrose also gives a geometrical interpretation. My description, given above, as "points representing lines" is a simplification. They are more accurately described as representing fields. For a null-twistor (a twistor describing a particle without spin - so helicity = 0; not to be confused with null-vectors describing massless particles, in this latter sense all twistors would be null) there is a line where the angular momentum-component vanishes, hence a line which can be interpreted as the world-line of a particle without spin. For other twistors the interpretation is much more complicated. The image is spread out, describing the motion of an extended particle.

Adaptation to curved space-time turned out to be complicated. "It may be felt, indeed, that twistors are not really appropriate for discussing conformally curved space-times at all. But to hold such a view would be to abandon the twistor programme as an approach to a more fundamental description of nature" ([1975], p.372). This was still a serious problem in 1981, but Penrose continued to believe in the twistor approach ([1981b], pp.580 & 585). He refered to the seven years that passed between the twistor description of a particle with spin 1/2 and that of a particle with spin -1/2, a transition which, in retrospective, was obvious. In 1986 (Penrose and Rindler) they had achieved a number of results, especially about the energy and angular momentum of gravitating systems.

The few indications that such a program, including

gravitational fields, might be realizable "encourages my own belief that twistors may reveal a hidden relationship between classical general relativity and quantum mechanics. Nature has, after all, chosen to weave her universe from these two constituents - and from others as yet largely unknown. Interrelationships must be present that we are unable now to perceive. And we are blinded not just by our lack of knowledge; our preconceived notions concerning space, time and quantum mechanics may be partly to blame" ([1975], p.403-404).

The basic idea of the twistor program is, I hope, by now clear. The subsequent literature does not add much to that. The program is of a triple nature:

(a) A reformulation of existing physics in different mathematics. The two formulations are equivalent, except for sign ambiguities. The twistor approach might in some cases provide an easier way of doing the calculations or suggest ways of calculating which would not have been found in the other approach (e.g. Penrose and Rindler [1984], pp.147-8).

(b) Although the two aproaches are at a certain (classical) level equivalent, they suggest different ways for changing the scheme to incorporate other phenomena or unify different parts of physics. The traditional space-time-vector approach lends itself easily to the idea of spaces of higher dimensionality. The twistor approach does not have this, but suggests a way of relating quantum theory and general relativity through the effect of fuzzy points when the twistor space gets deformed.

(c) Twistors represent a deeper level of reality than space-time points. This part of the twistor program is committed to an ontological realism with respect to twistors as fundamental entities, which are at the basis of both space-time and particles. The belief in this dual nature of twistors

is justified by the suggestion that both GR and QT might be derived from the twistors, that twistors evade the unphysical character of classical points, etc. Although this is expressed often in Penrose's work, it is defended more tentatively than the mathematical value of the twistor approach.

In the following, Penrose's work on singularities and time-asymmetry will be discussed. This has some relation to the twistor program, but is presented independently of the twistor mathematics.

3.2. Time's arrow, the specialness of the universe, and the interpretation of quantum theory.

Penrose has done much work on singularities in GR. He described a way to depict an infinite universe in a finite diagram, while retaining the structure of the light cone, thereby providing a picture of which points are causally related. Although this work started in the 1960s, the three items discussed here became the subject of publications mainly from 1976 on[3]. Those items are:

- the arrow of time (difference in past and future directions?);
- the "initial conditions" of the Universe (special?);
- the interpretation of quantum mechanics.

Penrose attempts to show how they are related. He proposes that there is a fundamental law which distinguishes between initial and final singularities by restricting initial ones. From this law, an arrow of time follows in a universe with an initial singularity. In the same framework there might be a relation between gravity and state-vector reduction which solves the interpretation problem without observers and without many worlds. According to Penrose, the existence of naked singularities would be much more alarming than the existence of black holes. "For whatever

unknown physics actually takes place at a spacetime singularity, its effects would be relevant observationally if and only if the singularity is a visible one" ([1978], p.230). He therefore made the cosmic censorship hypothesis that a physically realistic collapse will not result in naked singularities [1969]. The crux is the "physically realistic". This implies that certain solutions of the equations should have no physical relevance. But "this hypothesis should not exclude singularities of the big bang type - for otherwise one would presumably be ruling out the actual universe!" ([1978], p.233).

The problem lies in the conflict between the time-symmetry in the fundamental local physical laws as presently known and the manifest time-asymmetry. For the latter he points to seven arrows of time [1979]: the decay of the K^0 particle; quantum mechanical observations, although they can be formulated as time-symmetric at the level of subsequent observations; the increase in entropy; the absence of advanced radiation; psychological experiences, the difference between memories and the idea that we can affect the future; the expansion of the universe; and the difference between white and black holes. "I feel that such things [white holes, WBD] have nothing really to do with physics (at least on the macroscopic scale). The only reason why we have had to consider white holes at all is in order to save time-symmetry! The consequent unpleasantness and unpredictability seems a high price to pay for something [time-symmetry] that is not even true of our universe on a large scale" ([1979], 610).

Most of the arrows (except for the first and second) would be explained if there were a reason that the initial state of the universe was of comparatively low entropy. Since this cannot be located in the matter it must be in the geometry. In the beginning there was no clumping, so the

geometry was isotropic. Once there is clumping the isotropy gets lost (e.g. we have a strong sense of the difference between vertical and horizontal directions, due to the Earth) as well as the conformal invariance. The absence of clumping implies vanishing of the Weyl conformal curvature, which therefore could be used as an expression for the gravitational entropy. Penrose's hypothesis is that "there should be a complete lack of chaos in the initial geometry" ([1979], p.630), more technically: the Weyl curvature should vanish at any initial singularity.

"Some readers might feel let down by this. Rather than finding some subtle way that a universe based on time-symmetric laws might nevertheless exhibit gross time-asymmetry, I have merely asserted that certain of the laws are not in fact time-symmetric - and worse than this, that these asymmetric laws are yet unknown" ([1979], p.635). However, "it tells us to look for such asymmetries in other places in physics" ([1979], p.635), and one such place might be quantum mechanics. To summarize his position: There is time-asymmetry present. "It is, to me, inconceivable that this asymmetry can be present without tangible cause. ... In my own judgement, there remains the one ("obvious") explanation that the precise physical laws are actually not all time-symmetric! The puzzle then becomes: why does Nature choose to hide this time-asymmetry so effectively?" ([1979], pp.637-8).

Penrose expresses his view of the beginning of the universe in terms of entropy. The observed entropy per baryon (proton, neutron) is about 10^8 , which implies a total entropy of the observable Universe of 10^{88} . According to Penrose this is rather low. If all the mass would have been clustered in solar size black holes, the entropy "per baryon" would have been of the order of 10^{20}. If the universe as a whole - assuming for the moment that it is closed and about

the size observed today - would consist in its final state of only one black hole, it would have an entropy of 10^{123}, which he considers "a plausible estimate for the maximum entropy state of a universe of this type" ([1981a], p.247). This shows "how absurdly tiny this "observed" figure is in comparison with what it "might have been". This provides us with a measure of the degree to which the initial state was special" ([1981a], p.248). Since entropy is logarithmically related to the volume in phase space, the mathematical space of all configurations (one point representing one complete universe), one could calculate the specialness of our universe. Imagine such a space W,

> "whose points represent the various possible initial configurations of the universe. Imagine the Creator, armed with a pin which is to be placed at one spot in W thereby determining the state of our actual universe. ..., we are led to estimate that accuracy of the Creator's aim must have been at least of the order of
>
> $$10^{10^{88}} \text{ parts in } 10^{10^{123}}$$
>
> (this being the ratio of the volume to be aimed at to the total volume of W) i.e. one part in
>
> $$10^{(10^{123}-10^{88})} \div 10^{10^{123}}.$$
>
> ...Without wishing to denigrate the Creator's abilities in this respect, I would insist that it is one of the duties of science to search for physical laws which explain, or at least describe in some coherent way, the nature of phenomenal accuracy that we so often observe in the workings of the natural world. Moreover, I cannot even recall anything else in physics whose accuracy is known to approach, even

remotely, a figure like one part in

$$10^{10^{123}}.$$

So we need a new law of physics to explain the specialness of the initial state!"

([1981a], pp.248-9.)[4].

He discusses an "anthropic explanation", which fails since then a universe with entropy 10^{115} would have fitted as well, and it would have been "a vastly "cheaper" method than the one which appears actually to have been used" ([1981a], p.254). "Indeed, it would appear from this that the Creator was not particularly "concerned" about our existence, but was constrained in some very precise time-asymmetric way for some quite other reason. From this point of view, our present existence would arise merely as a by-product." ([1981a], p.255).

The preceding ideas also bear upon the interpretation of QT. According to Penrose, there are many more ways for a black hole to get formed (out of radiation, particles, television sets, ...)than to evaporate through Hawking radiation. The evolution of a universe can be described in a phase space describing possible situations by a point moving along a trajectory. If the point moves through a certain subspace there is a black hole present. There are more trajectories entering the subspace of universes with a black hole than there are trajectories leaving that subspace. This implies some trouble - also for the region describing universes without black holes - since a fundamental theorem, Liouville's theorem, says that volume in phase space is conserved, which might also be stated as that trajectories do not disappear or emerge. If they disappear in the subspace of universes with a black hole, there must be trajectories appearing in the rest of phase space.

This problem might be the clue to the interpretation of QT. As long as a system evolves according to the Schrödinger equation, it is described by a single trajectory. However, if "reduction" takes place, there are different possible outcomes, so different trajectories escaping from the region where the reduction took place. "The idea, of course, is that this volume increase should exactly compensate for the volume loss in the black hole region" ([1981], p.270). This provides, in principle, a quantitative link between the gravitational phenomenon of black holes and the quantum mechanical observation process.

In 1984 Penrose presented further ideas on "gravity and state vector reduction" [1986a]. Reduction is supposed to occur if the decrease in entropy involved in the reduction is at least compensated for by an increase in gravitational entropy. This seems to have testable consequences, like a prediction of minimal bubble sizes in bubble chambers, a measuring device to detect tracks of elementary particles ([1986a], p.144). As there is as yet no clear expression for gravitational entropy, the approach is rather tentative. In a postscript, influenced by R. L. Wald, Penrose suggests that it should perhaps be phrased in terms of the number of gravitons. This he later formulated as "that the linear superposition of states will cease to be maintained by nature as soon as the states become significantly differently coupled in to the gravitational field" ([1986b], p.50), where "significantly different" means "that the difference between the two Weyl tensors (...) is a spin 2 field whose graviton number count is at least one graviton" ([1986b], p.50).

4. S .W. Hawking's Quantum Cosmology Without Boundaries and Time.

S. W. Hawking has worked on singularities, black hole thermodynamics, and quantum effects when the curvature of space-time is large, especially by using the idea of topological fluctuations ("space-time foam") and Euclidean path integrals. Hawking summarized his work as "the problem of constructing a complete and consistent theory to describe these effects" ([1980b], pp.31-2.). In the present article, Hawking's application of these methods to the whole universe is considered. Hawking [1982, 1984a, 1984b] proposed in collaboration with J.B.Hartle (Hartle and Hawking [1983]) a method to calculate the wave function of the universe without assuming any boundary conditions (4.1). In (4.2) the implications for the arrow of time and the interpretation of QT is discussed, together with Hawking's expectation that theoretical physics will reach the end soon, perhaps "by the end of the century" ([1980a], Boslough [1985], 131).

4.1. The universe without boundary conditions.

The Hawking-Hartle proposal is that one calculates the wave function describing the probability of finding a certain three dimensional geometry with matter fields, a universe, by intergrating over a class of four dimensional extensions, all with a three dimensional geometry as their only boundary. This can be done in the case of a closed, compact three geometry, taking only compact four dimensional extensions. The use of a compact metric is essential. "By evaluating the path integral over compact metrics, one eliminates one of the two parts of physics, the boudary conditions. There ought to be something very

special about the boundary conditions of the universe and what can be more special than the condition that there is no boundary" ([1982], p.571).

The calculations are complicated and no model describing our universe with all its fields exists yet. There are some results, indicating that the density should - at least in a simplified model - be close to the critical density (Hawking and Page [1986]) and that most universes of this type undergo an inflationary phase (Gibbons, Hawking and Stewart [1987]).

The approach is clearly related to philosophical concerns, both in its view of boundary conditions and in its interpretations. Refuted is the claim of "many people" that "the boundary conditions are not part of physics but belong to metaphysics or religion. They would claim that nature had comlete freedom to start the universe off any way it wanted" ([1984b], p.258). According to Hawking, "what could be more reasonable than the boundary condition that the universe has no boundary?" ([1984a], p.363). And "if spacetime is indeed finite but without boundary or edge, this would have important philosophical implications. It would mean that we could describe the universe by a mathematical model which was determined by the laws of physics alone" ([1984c], p.358f.).

Hawking and Hartle gave the following interpretation: "One can interpret the functional integral over all compact four-geometries bounded by a given three-geometry as giving the amplitude for that three-geometry to arise from a zero three-geometry, i.e., a single point. In other words, the ground state is the amplitude for the Universe to appear from nothing" (Hartle and Hawking [1983], p.2961). But in the same article they also interpret it as "implying that the universe could continue through the singularity to another expansion period, although the classical concept of

time would break down so that one could not say that the expansion happened after the contraction" (Hartle and Hawking [1983], pp.2974-5.). In a subsequent article, Hawking seems to refer again to the first option, "It may well be therefore that the observed universe owes its existence to quantum gravitational effects" ([1984b], p.275). Something like this is needed, "if we want to understand the origins of the universe" (1984a, p.355). As I have argued elsewhere (Drees [1987]), the "nothing" in the "appearance out of nothing" is still "something" with physical existence, so the first interpretation seems too strong. A more modest and defendable interpretation is that this approach "determines the relative probability of universes corresponding to different classical solutions" (Hawking [1984a], p.377).

4.2. Time, quantum reality and the end of physics.

Although Hawking agrees that the big bang is an edge in the standart model, which can be interpreted as "time began at the Big Bang" ([1984c], 356; [1984d], 12), he is not satisfied with such an edge. It would mean that there were boundary conditions needed aside from the laws. In his model for a universe without boundaries "time ceases to be well defined in the very early universe just as the direction "north" ceases to be well defined at the North Pole of the Earth. ...The quantity that we measure as time had a beginning, but that does not mean spacetime has an edge, just as the surface of the Earth does not have an edge at the North Pole" ([1984c], p.358; [1984d], p.14).

Hawking defends the absence of an overall arrow of time, opening an article on this topic with "Physics is time symmetric" ([1985], 2489). He shows that for his path integral approach the total wavefunction of the universe has

the same time-symmetry as those of quantum field theories. This leaves him with the problem of explaining why "the Universe that we live in certainly does not appear time symmetric" ([1985], p.2489). He holds that there are two arrows of time, the thermodynamic arrow (future = direction of entropy increase) and the cosmological arrow (future = direction of expansion of the Universe). He argued that these two arrows should coincide. Hence, one would see entropy decreasing in a contracting universe. In that case the direction of time would be defined the other way round and there would be again both expansion and entropy increase. In a "note added in proof" [1985] Hawking agrees with the conclusion reached by Page [1985] in the context of Hawking's theory, that the thermodynamic and the cosmological arrow need not to coincide and so there is no reversal of the thermodynamic arrow at the moment of maximum expansion. Although Hawking maintains that the total wave function must be time symmetric, it might be that individual classical solutions, which correspond to components of the wave function, are not symmetric.

Hawking criticizes Penrose's proposal about the Weyl curvature for initial singularities as "ad hoc", "putting in the thermodynamic arrow by hand"; as unclear in the absence of a theory of quantum gravity; and "Penrose's proposal does not explain why the cosmological and the thermodynamic arrows should agree" ([1985], p.2490). The last criticism lost its force after the "note added in proof". Besides, Penrose offers an argument why the cosmological arrow and the thermodynamic arrow concur near initial singularities: both arise as a consequence of his "new law". The second objection is correct but holds for all current theories. It neglects Penrose's related work on the interpretation of quantum theory and on twistors which is

in a way an attempt at quantum gravity. The first criticism, the "ad hoc" character of Penrose's proposal, is circular. Hawking objects to making a difference between past and future. This criticism would be correct within Hawking's program, where the arrow of time is believed to be something not part of the basic structure of reality, therefore following from the theory. However, the criticism misses the point of Penrose's program. Penrose is impressed by the asymmetry of time in nature, "one of the long-standing mysteries of physics" (Penrose [1979], p. 581), an aspect of reality which has escaped physical description so far. That his theory makes a distinction between past and future singularities is not surprising; this is essentially what he is trying to do. Within his view, one could object to the way time asymmetry is introduced, but not to the introduction of such an arrow. Hawking's criticism is from outside, from a different perspective on the characteristics of reality.

The remark about components of the wave function brings us to the other issue, the interpretation of quantum theory. Hawking adhers to the Many Worlds Interpretation, although he finds the name misleading. It "simply involves the use of conditional probabilities, that is, the probability that A will occur given B" ([1984a], p.336). There is no problem of interpretation "and my attitude to those who argue about the interpretation of quantum mechanics is reflected in a paraphrase of Goering's remark: 'When I hear of Schroedinger's cat, I reach for my gun' "([1984a], p.337). He applies this interpretation to his wave function of the universe, which corresponds to a whole family of classical solutions. In a guantum state that combines two states peaked around two different classical solutions "measurements made by the intelligent beings in the first universe would correspond to the properties of the first

classical solution and measurements made in the second universe would correspond to the second solution" ([1984a], p.377). The wave function gives the relative probability of the different classical solutions. This implies that within such a solution, one cannot doubt its existence. As Hawking's collaborator Don N. Page said, an observer can not directly become aware of his "absolute probability (or, more accurately, measure) of existence" (Page [1985], p.2498). Hawking stated in his inaugural lecture [1980a] that "we would have to abandon the view that there is a unique universe that we observe. Instead, we would have to adopt a picture in which there was an ensemble of all possible universes with some probability distribution. This might explain why the universe started off in the Big Bang in almost perfect thermal equilibrium, because thermal equilibrium would correspond to the ... greatest probability. To echo Voltaire's philosopher Pangloss, 'We live in the most probable of all possible worlds' "([1980a], Boslough [1985], pp.145-6). If I understood him correctly, it would perhaps be even more adequate to say: most probably we live in the most probable of all possible worlds; we also live, but less, in the least probable world compatible with our existence.

The end of physics?

In his 1980 inaugural lecture "Is the End in Sight for Theoretical Physics" Hawking expressed as his view of the aim of theoretical physics that it should be both an explanation of the unique initial conditions and the removal of arbitrariness (e.g. physical parameters) from the physical laws. If the boundary conditions for the whole are that universe has no boundary conditions, "all that we would then need is a completely consistent theory of quantum gravity and the other interactions, and we would be able to

predict everything, at least in principle" ([1984a], 378). He expects that these laws will be approached by steps, within a few decades, say from theories of the weak and strong interactions, through supergravity theories. But complete predictability is qualified (e.g. in [1980a]) by pointing to the quantum uncertainty principle and the complexity of the equations. "Thus we would still be a long way from Omniscience" ([1984c], p.358; [1984d], p.14).

5. Discussion.

According to Lakatos science can be described as consisting of various research programs, series of theories described by a certain continuity. The continuity is visualized as a hard core and a positive heuristic. A program is characterized by its hard core, the set of hypotheses which are kept fixed. Other hypotheses can be added or changed according to theoretical or empirical needs. So in the "protective belt" one finds the major development within the program. The development is not haphazard, but quided by a long term research policy, the "positive heuristic". Theoretical science has a relatively autonomous development, guided more by the awareness of the unsatisfactory character of the theory at each moment than by specific experimental results. And in that theoretical development mathematics has a central role.

If one looks to the works of Penrose and Hawking with this scheme of mind one sees that they exhibit these characteristics of a program. As far as I can see it, they agree for their hard core in accepting general relativity, quantum theory and thermodynamics as valid within their domains, and in accepting the standard cosmological observations (redshifts, etc.). Hence, they both accept the

big bang model as valid "after the first fraction of a second". Therefore, they also agree on the standard problems of this model, like the need for explanations of the observed homogeneity and the inhomogeneities in the universe. They both object to the Kopenhagen interpretation of quantum physics since the notion of an observer does not make sense for the universe as a whole and is at odds with their implicit view of reality. They share the belief in the need to integrate the different fundamental theories GR, QT, and thermodynamics.

For Penrose, the specific element in the hard core of the twistor program is that twistors are the basic entities of his theories. For Hawking, the Euclidean path-integral method is, in the context of this work, taken for granted. However, such "hard core" elements are closely related to their general view of reality, since the twistors are supposed to be more basic than points, while the path integral goes with an attitude which takes all possibilities of reality seriously.

The differences are most exlicit in their positive heuristics, especially in preferences, as well as in the broader background of convictions about reality and about the attainable level of explanation. Both Penrose and Hawking use realistic language, implicitly assuming that a stronger mathematical formalism implies a better explanation and refers to entities which are closer to the "deep structure of reality", thereby using an instrumentalist argument for a realist position. Penrose seems guided by a belief in the reality of time and of the arrow of time, a physical difference between past and future. Besides, he has a strong preference for discrete entities. This shows up in his objections against the continuum and his long term goal of a combinatorial formulation of the laws of physics. In this sense, his approach has a Pythagorean flavor. Penrose

also allows for unrealized possibilities, as is most clear in his description of the Creator picking one universe out of many possibilities. Hawking appears to be guided "sub specie aeternitatis" by the whole of reality at once, as in the standard formulations of general relativity. This implies that time, evolution, novelty, and so on, are mere consequences of our description from within. What looks like a beginning of the universe is not one, if seen from the right perspective. Besides, for Hawking everything that is possible is also actual, a kind of necessitarianism, while for Penrose there remains an element of chance, both in his view of the initial conditions and in his view of reduction of the state vector in quantum mechanics.

The different programs have partly different problems to solve. Penrose needs to explain transitions in reality independent of "observers", having a definite reality available for macroscopic observers, while Hawking needs to argue why observers observe a definite universe in stead of the "real" fuzzy superposition of many states which is his view of reality. As another example, notice that for Penrose the question is why the fundamental asymmetry in time is mostly hidden - in other words, why time-symmetric physics (Newtonian, general relativistic and quantum physics) works so well for most phenomena. For Hawking the apparent asymmetry needs to be explained on the basis of a symmetric theory and symmetric boundary conditions. This shows that they also disagree in their view of the data. For Penrose the asymmetric phenomena are "hard" data, in need of description and incorporation in the framework of physics. For Hawking, they are illusions, which have to be explained away. This difference in perspective show up clearly in Hawking's criticism of Penrose's introduction of an arrow of time, a criticism which has its force in one perspective and not in the other. There is, of course,

consensus about many implicit criteria of rationality and good science. However, there is also a difference in criteria, especially in the more "subjective" ones like what is aesthetically preferable.

Twistors and path integrals are at first equivalent to previous approaches, mere reformulations. However, the relevance of such reformulations is obvious in these two examples, as they provide different suggestions for what is mathematically feasible, aesthetically acceptable, and hence "natural" to do. Besides, they suggest different ways in which the scheme can be changed, and so might lead to theories which are no longer equivalent at the next level. Some equivalence in results is to be expected in any case, as they both try to encompass the successful standard theories of general relativity and quantum theory. However, that might be achieved in quite different conceptual schemes.

They both presuppose that the unity of nature implies a unity of description, in this case of quantum and space-time physics. Hawking states in his inaugural lecture [1980a] that there are "at least three possibilities", a complete theory, an infinite sequence of theories, or no theory and no description and prediction beyond a certain limit. The "at least" makes my speculation about his view less sure, but apparently he does not take seriously the possibility that there might be two equally defendable theories or sequences of theories which are different in their conceptual structure. A point of philosophical interest might be whether it will be possible to make a choice on criteria which are acceptable to both programs. Although they have elements in common, they might both produce theories which are acceptable according to those shared criteria, for instance the reproduction of GR, QT, and thermodynamics in their respective domains of validity. In that case, the two

approaches would lead to theories which are empirically equivalent.

That leaves open two possibilities, either they are in a more complete sense equivalent, and there might exist ways of translating the concepts of the one into the other,or they might be fundamentally different, and so conceptually (metaphysically, logically) incompatible. For the possibility of equivalence, one might point to the equivalence in quantum physics of the wave formalism invented by Schrödinger and the matrix formalism of Heisenberg or in general relativity the standard description of space-time as a four-dimensional whole "at once" and alternatively - at least in many cases - as a three-dimensional "space" evolving through time. There are more examples of such equivalences of approaches which differ in their view of time. For path integrals the whole path is discussed, while in using a differential equation and boundary condition one goes through the history step by step. The evolution of a system in time can be described by a trajectory in phase-space, which describes the whole history at once. Might it be that one could do physics both ways, either "from within time" or "sub specie aeternitatis"?

Even granted the possibility of these two approaches, from within time and from outside it, and the existing examples of "equivalences", it might be that the two programs discussed in the present article do not produce theories which are equivalent in such a way. I conjecture that this is the case, as the differences in their view of time and its reversability, the nature of quantum reality, and the initial conditions of the universe are very fundamental. If the case for this conjecture could be strengthened, the two programs discussed in this article might be concrete examples of programs producing theories which are "logically incompatible and empirically equivalent" (Quine

1970). To prove this, much more work needs to be done both on their empirical equivalence and on their logical incompatibility. If this turns out to be the case, it strongly supports ideas about "underdetermination", while raising questions about "critical realism" and all kinds of consensus and convergence arguments for such realism.

Less problematic is that they both want to go ahead beyond limitations of the standard theory. Although the laws of physics break down at singularities, "I do not believe that physics itself breaks down at a space-time singularity. It is just that the laws that govern their structure are presently unknown to us" (Penrose [1986a], p.137). The same attitude is also present in Hawking's work, for instance in his expectation of a complete theory. Using a distinction made by M.K.Munitz [1974], they seem to hold both a methodological principle of sufficient reason - one should seek reasons - and a metaphysical principle of sufficient reason - there must be such reasons. They even hold a third one, such reasons are in principle knowable.

Lakatos stated: "One may formulate the "positive heuristic" of a research program as a "metaphysical" principle" (Lakatos [1978], 51). In the two cosmological programs discussed in this article, this is true in a strong sense. Lakatos uses "'metaphysical' as a technical term of naive falsificationism: a contingent proposition is 'metaphysical if it has no 'potential falsifiers'"(Lakatos [1978], p.47, n.2). In the examples discussed in the present article, the ideas are not only "metaphysical" in the sense that their guiding ideas are from within each program beyond dispute, but also metaphysical in the stronger classical sense, as they are about issues like the relation between actual and potential existence, the nature of space and time, discrete entities or continua, contingency or necessity of the Universe.

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Notes

1. Although this article discusses only work of Penrose and Hawking, there are many others contributing to the same programs. Besides, there are other programs - or more diffuse activities - as well. However, Penrose and Hawking are two key figures in their programs and their programs are major contributions to contemporary discussions in scientific cosmology, as could easily be shown from the Science Citation Index and conference proceedings.

2. Spin networks, spinors and twistors can be found in articles by Penrose from 1959, 1960, 1967, 1968, and elsewhere, conformal transformations were discussed in 1963, 1964a, 1964b.

3. The first presentation of the relation between the Weyl curvature and time-asymmetry that I came across was at a conference in Pakistan in 1976, Penrose [1977]. The relation

between time-asymmetry and the structure of singularities was conjectured in public in 1973, Penrose [1974].

4. To get a feeling how large the number involved is: to write it down, using only one elementary particle for each zero, even a trillion times the total amount of particles in the observable universe would be insufficient.