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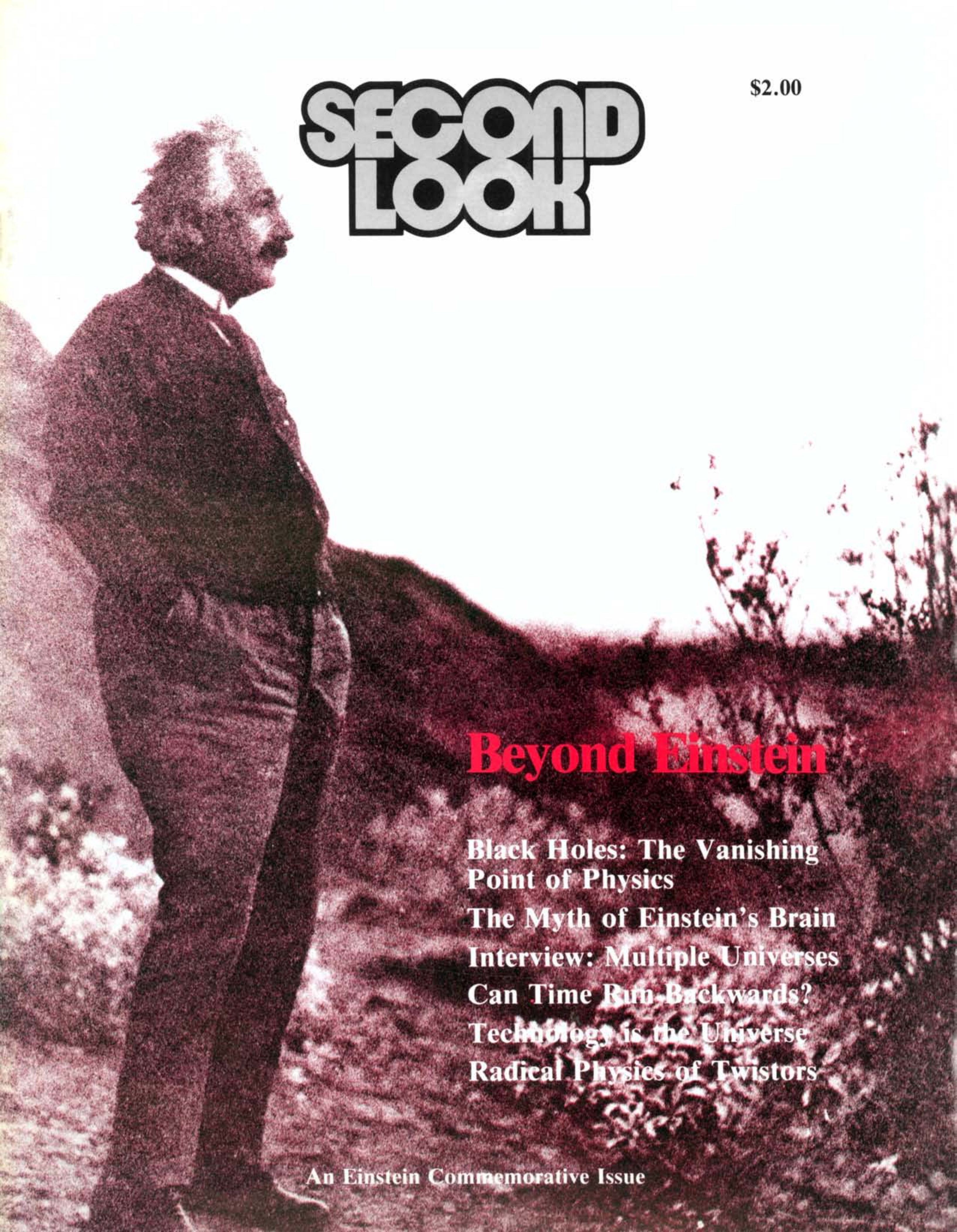


Beyond Einstein

Black Holes: The Vanishing Point of Physics

The Myth of Einstein's Brain

Interview: Multiple Universes

Can Time Run Backwards?

Technology is the Universe

Radical Physics of Twistors

An Einstein Commemorative Issue

The Radical Physics of "Twistor" Theory

by Roger Penrose
Introduced and compiled by
Robert K.G. Temple

There are two main areas of basic physics today, the quantum theory that is used in atomic physics, and relativity theory, which is of space and time. No one has yet managed to combine them or even make them compatible. Many of the current attempts to do so are known as "attempts to quantize gravity." Gravity is the main subject of Einstein's general relativity, and no one has ever been able to reconcile the fact of its existence with the behavior of atoms and atomic particles. It is thought by many scientists that quantum theory, which describes atomic particles, *must* be able to describe gravity too; the fact that we haven't been able to do this is assumed to be because we are stupid. That is why they say we have to "quantize gravity." Gravity is thought of as a fierce bucking bronco which must be tamed and brought under control so that quantum theory can ride it. "Quantizing gravity" is thus the process of taming the bronco, or may be viewed as "tranquilizing the lion" by shooting a drugged dart into it. Whether gravity, even if tamed, would break free again from its quantum fetters and savage its trainer must be one of the recurring nightmares of those intrepid physicists who dream of bringing gravity under control.

Nowhere in the world of physics today is there a more fascinating attempt to marry Einstein's work with quantum theory than under the auspices of Professor Roger Penrose, at the Mathematical Institute of Oxford University. He is a modest, soft-spoken man driven by intuition and a profound restlessness about our conventional assumptions. Many people throughout the world, in physics and mathematics, do not understand what he is doing. He is the founder of a strange and exciting new approach to understanding reality called "twistor theory."

A review appeared in ***Science*** Magazine (March 19, 1976, p. 1164) of a book which Penrose co-edited, entitled **Quantum Gravity.** The reviewer remarked: "To me the most exciting approach is that of R. Penrose with his twistor theory. . . . While representing a radical change from the conventional view of space-time, (his) technique holds the promise of making contributions not only to a quantum theory of gravity, but also to a theory of elementary (atomic) particles. The unusual and difficult mathematics required, together with the scarcity of publications by the group around Penrose, have prevented ready access to the theory by most physicists, but I believe this approach holds as much hope for an eventual quantization of gravity as any of the more conventional approaches."

There is no doubt that if he can succeed in his aims, Roger Penrose's name will be well known in the future to ordinary people as a man who achieved a major breakthrough in science. But what are his aims? What are his methods? What is his theory? Although Penrose has published a moderately non-technical contribution to the remarkable book **The Encyclopaedia of Ignorance** (to be reviewed in a future issue of SECOND LOOK), at the time of writing, no genuinely non-technical account of Penrose's work has ever been published anywhere. SECOND LOOK approached Penrose not long after the British ***New Scientist*** Magazine (entirely a coincidence), and both magazines have made an arrangement to share publication rights to an article by Penrose, which forms part of the article below. However, we have constructed our article from a great deal of additional material as well, in an attempt to present a fuller account and to get around some of the horrendous problems of explaining this most mathematical of all physical theories in a way intended to be comprehensible to everyone. A lengthy taped interview with Professor Penrose both forms part of the main text itself (without attribution) as well as being occasionally interspersed in recognizable form as follows:

TEMPLE: You are developing twistor theory as an attempt to quantize gravity? You are really trying to use quantum theory and what we know about it to do something with relativity theory? Is that ideally what you'd like to do?

PENROSE: If you like, quantizing gravity is part of what we are trying to do here, but it's not the main driving force. We are also concerned with other parts of physics, elementary particle physics for example. What we are trying to do is to combine the concepts of space with the concepts that are involved in quantum theory, to unite them together in a much more unified way. So in that sense it is close to what one is trying to do in quantum gravity.

TEMPLE: So in fact that's just a subsidiary thing—that you are also trying to quantize gravity. But basically, you are trying to get a theory of the Universe?

PENROSE: Yes, I suppose that's right. Let's say that quantum gravity has to do with fitting quantum theory and *general* relativity, which is curved space-time, together in some unified theory. Twistor theory is much more concerned with taking quantum theory and *special* relativity (the earlier and simpler part of Einstein's relativity) and reformulating things. You see, a physicist wouldn't normally say you should do anything here. They'd say: "Special relativity and quantum theory? Well, we know about them now." The driving force here is not so much something which is forced on us by physical requirements. It's a more nebulous thing, the feeling that one really needs a reformulation of physics. It's not something which one is driven to in a very clear way. So I think sometimes people have difficulty—or at least they certainly had in the early stages of this theory—difficulty in understanding quite why I was doing what I was doing. It's not like in quantum gravity, where we could see there was a real physical problem, to put these two things together.

TEMPLE: So you are really motivated by restlessness?

PENROSE: Yes, that's right. The motivations are not so clear, physically clear, as they are in quantum gravity.

TEMPLE: I see. So a lot of your friends are motivated by much more mundane matters such as the desire to quantize gravity. And you are interested in solving the riddles of the Universe.

PENROSE: I wouldn't call the others mundane. But my view point is different I suppose . . .

TEMPLE: You're really working with your intuition. In fact, intuition really gave birth to twistor theory, didn't it?

PENROSE: That's partly true. Well, there were lots of rather vague mathematical and physical ideas—inconclusive things which seem to point in this direction. In the early days when people asked me what I was doing, it was very hard to try and explain, because there were a lot of motivations, but no one of them was by itself all-persuasive. And it was only that everything together seemed to make me go in this direction.

TEMPLE: You know what it reminds me of? And the work of a lot of scientists and mathematicians reminds me of? It's as if the end results of their intellectual careers in some strange way pre-existed and drew them to the construction of the edifice on which that conclusion would then be able to rest, as if the capstone were there as they were trying to build up to it. You get that feeling?

PENROSE: Yes. This is on dangerous ground. But I know what you mean.

TEMPLE: You have a teleological worldline!

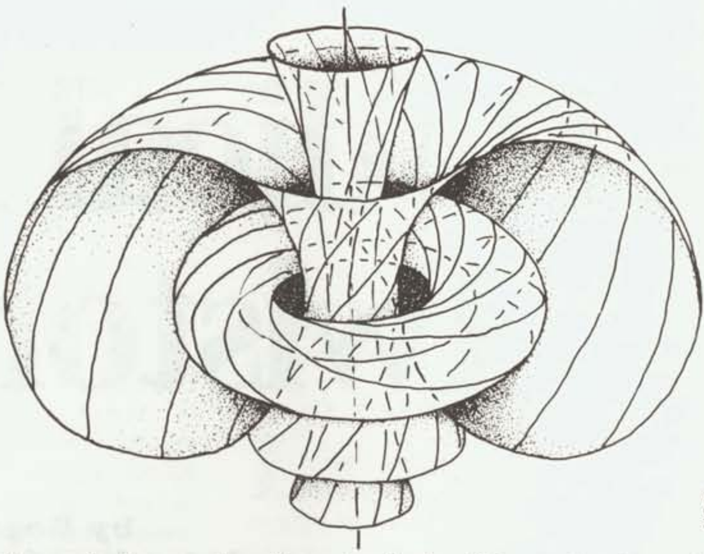
(LAUGHTER.)

PENROSE: Well, I am sure there are many motivations which are very hard to articulate. I have some hobby horse too about Newton. He had this very peculiar theory of light, where it behaved as a sort of combined wave and particle, which for a long time was thought to be wrong, until, with the advent of quantum theory in this century, it turned out to be much closer to the truth than had seemed possible.

TEMPLE: Do you think Newton was intuitive?

PENROSE: Well, I think there may have been lots of things that he was sensitive to. He couldn't articulate what they were. But he was obviously very sensitive to the way things are, and he must have felt even for reasons that he knew were partly wrong and partly impossible to say that this was what light was really all about.

TEMPLE: How many leading physicists really worry about the concepts underlying their work?



MOSS

Penrose's theory describes atomic particles and subatomic "empty" space, and their interaction in terms of "twistors," rather than points in Einsteinian space-time.

PENROSE: Of course, they may worry sometimes without articulating their worries. There are a lot of things involved which are very hard to say, and which you don't really know yourself. Einstein was certainly very troubled by this kind of conflict in many ways. This came out at an Einstein centenary conference at Princeton which I attended earlier this year.

Professor Penrose now writes:

In what must be one of the most compelling introductions to a work of popular science, Sir Arthur Eddington, in his Introduction to **The Nature of the Physical World** (1927), remarked that, while relativity had caught the attention of the public with its uprooting of conventional ideas of space and time, another revolution had also taken place which he himself regarded as even more remarkable. And yet it had passed almost unnoticed by the world at large. He was referring to the discovery that seemingly "solid" matter, like his writing-table, was really composed almost entirely of empty space! Far removed from everyday experience as that description might be, it accords excellently with the scientific facts. Indeed, Eddington referred to his "two tables," one being the commonsense "solid object" of our immediate sense, and the other his "scientific table," composed ultimately of mathematical entities: "My scientific table is mostly emptiness. Sparsely scattered in that emptiness are numerous electric charges rushing about with great speed; but their combined bulk amounts to less than a billionth of the bulk of the table itself . . . my scientific table with its substance (if any) thinly scattered in specks in a region mostly empty . . . is nearly all empty space—space pervaded, it is true, by fields of force, but these are assigned to the category of 'influences,' not of 'things.' Even in the minute part which is not empty we must not transfer the old notion of substance."

In the 52 years since Eddington wrote his book, much attention has been paid to, and much has been learned about, those minute particles of "solid" matter within atoms which constitute no more than one part in 1,000,000,000,000,000 of the volume of an object such as a table. This is less even than Eddington thought. Comparatively little attention, however, has been paid to understanding the empty space of which the table is actually almost entirely composed. There are probably two reasons for this. First, there is the feeling in physics that we already completely understand the nature of empty space because a description of it is given to great accuracy by the geometry of Einstein's special relativity. But on the other hand, and this is a strangely opposite reason, there is an almost total lack of a truly *deep* understanding of the nature of empty space.

According to standard theory, empty space is seething with activity at the submicroscopic level, and if one accepts conventional ideas of quantum theory, there would seem to be an infinite amount of energy present in any ordinary small region of space. But Einstein's general relativity tells us that this cannot really be so, since this would imply that the Universe was infinitely curved so something is wrong with standard theory. Even if Einstein's ideas could be correctly combined with the quantum theory, fluctuations in the gravitational field at the tiny level would be large enough to make the concept of space-time go wrong. These fluctuations would be big enough to cause the geometry itself to go haywire. This geometry, or metric, is a concept which is essential to one's picture of space on the ordinary scale. On a small enough scale, empty space becomes foam and turbulence and is no longer continuous. This is basically an idea due to Professor John Wheeler. And in a certain sense he is rather conservative about physics, although he's very radical as well. But he likes to carry *existing* theory absolutely as far as it can go, so the idea is to say: "Don't change general relativity, don't change quantum theory, just extrapolate each as far as one can and see how far we can carry the ordinary concepts of space and time." I mean how far down, to the small dimensions.

These tiny, submicroscopic dimensions are so small that they are twenty orders of magnitude smaller than the nuclear particles. If a nuclear particle were the size of the earth, this dimension would be about the size of a hydrogen atom. In other words, the scale at which, according to what is now the conventional view, geometry goes haywire is so small that it is a fraction of a centimeter described by a decimal fraction of 1 preceded by thirty-two zeros. I will write it out, to stress the smallness of the size:

.000000000000000000000000000000001 centimeter.

Obviously, when we discuss this size, we cannot always use 32 zeros, because they take up too much space. Therefore, we use the scientific convention for abbreviating things like that by writing 10^{-33} cm. This makes life much easier. So, in using that for the rest of this article, the reader will know what I mean by it.

Now imagine yourself at a dimension of 10^{-23} cm. That is nicely in between 10^{-33} and the size of nuclear particles. Space and time, according to the conventional view, is still absolutely smooth, continuous — you wouldn't notice a thing different about it. Yet particles, which are the relatively granular things which make up our universe — as far as we know it — and make up what little actual "substance" there is in Eddington's table, are (looking up at them from this lower size) huge, vast, and barely discernible clouds. And yet what appear from "underneath" as vague clouds constitute the "solid things" that we actually see in daily life. There seems to me to be an absurd discrepancy between these two ideas. Why is it that the only vaguely solid things we have left in physics should be these just barely discernible clouds? Nuclear particles in their behavior are really much more like identical building blocks than they are like clouds. This is actually a point made by Professor John Wheeler, who originally talked about these clouds. But whereas Wheeler thinks that somehow quantum theory will mysteriously solve this problem, I think there is a real conflict in physics about it.

It really seems that we are as far away as ever from understanding empty space. So, what prospect is there of understanding the detailed nature of the particles which inhabit that space if we do not understand the space itself? But it is not necessary to consider such absurdly tiny dimensions to see that there is a conflict between our geometrical pictures and actual physical behavior. On the scale of atoms, or their smaller constituent particles, our geometrical picture of things becomes quite inadequate. At this level we cannot really localize objects in space. This incredible fact was first described in 1927 by Professor Werner Heisenberg. He called it the Uncertainty Principle, and for this he was awarded the Nobel Prize.

But perhaps it is not geometry itself that is at fault in our conceptions of the minute scales. Perhaps it is only the specific space-time geometry that we have become accustomed to on the large scale of daily life, and our own limited imaginations, which are at fault. We just simply assume that our conventional notions must hold good down to the submicroscopic level. The impressive accuracy of our experiments with nuclear particles seems to show that our ordinary ideas of space and time must hold good down to one hundredth part of the diameter of a nuclear particle. Yet is this really so?

At the level of celestial motion, Einstein's theory may be regarded as essentially a reformulation of Newton's. It

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gives a more profound view of the nature of space, and a considerably more accurate one for the description of very strong gravitational fields. But it doesn't mean that you have to throw out Newton's formulae for motion. You can still use these, even when general relativistic phenomena become significant. You can just put in correction terms to bring Newton's formulae into line with Einstein's, and often it's a good way of calculating. When they launch a rocket to the Moon, they use Newtonian theory and add a little bit of correction. They don't have to throw Newton away and just use Einstein. And this would be my view of how one would treat many things in physics. Even if the continuous, smooth, normal space-time would break down and no longer be an accurate view, you could still use it and get very good answers by simply making corrections to it. You could do this increasingly all the way down to 10^{-33} cm.

One of the main ideas of twistor theory is that space-time points are not initially present in the theory.

So I am suggesting that some geometric *reformulation* may represent a key to understanding the geometry that governs behavior at the submicroscopic level. And in order to be able to reproduce the successful physics of our day in this new scheme, this reformulation must incorporate both the mechanics of quantum theory and the geometry used in Einstein's special relativity. Later on, Einstein's general relativity and its features must also be accomodated, but this would be needed in practice for only a comparatively small number of physical phenomena.

The reformulation I am talking about means a change of framework. It is one of the basic ideas of twistor theory to provide such an alternative framework for physics. In fact, it is a long-term aim of twistor theory to eliminate from physical theory altogether the concept of a continuum, or "smooth" space. Then the description of natural phenomena would be based on an entirely different principle. One of the main ideas of twistor theory is that space-time points are not initially present in the theory. Points are taken to be derived objects, the twistors themselves being more basic. We picture these truly basic things, twistors as I have named them, as something in free motion and which are spinning (or twisting). Twistors are not physical particles at all, but for visualization purposes, we may conceive of them as particles which have absolutely no mass.

Twistors are abstract mathematical entities. We describe nuclear particles *in terms of* twistors. The photon, or light quantum, may be described in terms of a single twistor. Electrons seem to require two twistors for their description. The heavier particles require three, or perhaps four or more. But the twistors themselves are not particles. But neither are they points. From the twistor viewpoint, instead of talking about points, you talk about twistors. The whole of the geometry of special relativity could be entirely reconstructed on a twistor basis. The essential aim of twistor theory is to try to describe as much as possible in purely *twistor* terms. The idea is that the more fundamental the level at which physics is being treated, the more relevant will be the descriptions in terms of twistors and the less relevant will be those given in terms of space-time geometry. In other words, as you descend lower and lower in size, "space-time thinking" gives way to "twistor thinking."

As part of the program of myself and my colleagues, a twistor method of describing atomic particles has arisen. Massive particles, such as electrons or protons, can be handled as well as the massless particles such as photons. This work is continuing. A more detailed and ambitious aim is to express conventional quantum field theory in twistor terms in an attempt to rid that field of a mathematical nonsense which plagues it at the moment—the fact that in the solutions of the equations infinities keep coming up in the answers. There are still many mathematical difficulties which stand in the way of this program.

In order to explain more precisely what a twistor actually is, it will be necessary for me to refer to one mathematical concept which simply cannot be avoided. It is essential to realize what a *complex number* is. This is a specifically defined kind of number. The word "complex" is not used loosely or casually. It means something quite precise. But it should be possible to understand it without too much difficulty. This is absolutely essential, or we cannot proceed.

A complex number is a combination of an ordinary "real" number and what mathematicians call an "imaginary number" (which does exist although it is called "imaginary"). The simplest imaginary number, which is represented by the small letter i (for "imaginary"), is a square root of -1. Most people will remember from school that you are not supposed to be able to take the square root of a minus number because that "doesn't make any sense." However, these imaginary numbers turn out to be fundamental to a description of reality.

Complex numbers are combined "real" and "imaginary" numbers which are even more useful and more fundamental than the imaginaries on their own; they actually combine the "seemingly possible" and the "seemingly impossible" together and are very powerful and are absolutely fundamental to twistor theory.

There is a simple, standard notation in which complex numbers are written. You may recall that in algebra, numbers are often represented by the letters a and b. I have already told you that the imaginary, the square root of minus one, is represented by the letter i. Complex numbers, then, are simply represented typically by $a + ib$, where a and b are ordinary "real" numbers and where the symbol i stands for a quantity whose square is -1. Such complex numbers can be added, subtracted, multiplied and divided (except by zero) in the ordinary way, and they turn out to have many surprising mathematical advantages over real numbers. Complex numbers have a mathematical "life" and "reality" of their own that can be fully appreciated only after one attains considerable familiarity with their properties. Sometimes things

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in mathematics have a rather artificial reality in that they are invented only for convenience and have a limited scope. But sometimes they seem to take on a life of their own. And complex numbers are a very good example of this. The concept of a real number evolves out of necessity — people like to measure things. In order to have a nice way of describing length, in a coherent way, this concept of a real number was invented.

But even a real number involves incredible abstractions from what one can actually do, however. One can not actually measure things which are infinitely small. One can't measure the distance of $10^{-\text{one million}}$ centimeters (a decimal with 999,999 zeros in front of the 1). But yet we need to have such things existing in some mathematical sense, in order to have a nice coherent scheme. So real numbers involve this kind of abstraction already. When one gets used to them one begins to think that there is such a thing as $10^{-\text{one million}}$ cm. even if you couldn't get there. But that might not be true, you see. But the mathematics acquires a reality of its own which one tends to take over into the physics. In the case of complex numbers I think this is a good thing. It took people a long time to accept them, although they could see that such numbers were very useful things in mathematics which seemed to have an existence behind the scenes.

PENROSE: The mathematician Karl Gauss was the first to take the plunge. He said in effect: "These numbers are really just as good numbers as real numbers and you can make perfectly good mathematical structures out of them. In the mathematical sense they exist as strongly as the real numbers do." And then they turned out to have so many remarkable properties beyond what they were invented for. They were invented to be able to solve some quite simple equations. And then, lo and behold, they do all sorts of other things completely free. They solve *all* algebraic equations, not just the ones they were invented for. They do all sorts of things for analysis, and they have unified lots of ideas. It is something one gradually gets to appreciate. They have a reality quite beyond what they were invented for.

TEMPLE: Which really must mean therefore that, far from being constructs just to get around a solution of an equation, we have stumbled on an underside of the Universe?

PENROSE: I think that's right, yes. You find in certain concepts of mathematics that they have a life of their own. And other concepts seem to be dead. And the view I like to take is that there is a very close inter-relationship between physical reality and this kind of mathematical reality, and that the reason for the one is the other in a sense.

The twistor description leads to a radically different view of the possible nature of space-time.

TEMPLE: So this is what leads you to suppose that some of these things must mean something other than just in the abstract? They must stand for, symbolize, or represent something, if only we could conceive of that?

PENROSE: Yes. That's right. So even if something may seem like a mathematical construct, sort of an invention, if that thing has a mathematical life, then perhaps we should attach a little bit more physical reality to that whole idea.

There is a remarkable inter-relation between geometry and the complex numbers in twistor theory. The complex numbers which are so vital in the description of twistors are intimately and inextricably tied in with the geometry of the resulting space and time. The strength of the twistor description of things resides in a number of extraordinary mathematical facts such as this which it is very hard to believe could be simply "accidental." These facts are all concerned with complex numbers in various ways. Such a wide variety of 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.

The twistor description leads to a radically different view of the possible nature of space-time. Space-time points are not initially present in the theory at all, and when they are introduced they become fuzzy and are not true points anyway. The twistor view transfers to the very concept of space-time points themselves the uncertainties otherwise so baffling in quantum theory descriptions.

It has not been possible for me to describe fully here the precise nature of twistors themselves. They are mathematical abstractions somewhat between the concept of a point and the concept of a particle, but, I believe, more fundamental than either. Both points and particles may be interpreted or described in terms of twistors. Although it would be too complicated to go into further descriptions of this kind here, I have provided a "drawing of a twistor" if you would like to see what a twistor looks like in terms of ordinary space-time descriptions. The whole picture is to be thought of in motion moving "up" the page with the velocity of light. I could, however, express the space and time instead in terms of twistors, and my attitude would be that the twistor picture of space and time would be more fundamental than the space-time picture of the twistor. However, people like a picture, and so here it is, although it is simplified.

Twistor theory is largely incomplete, but it offers considerable hope for a quite new approach to the basic problems of theoretical physics. It seeks to explain both the minute particles and the vast empty space that are together needed to compose Eddington's "scientific writing-table." The twistors are seen to be more basic than either. Twistors are abstract mathematical entities whose properties are forced on us by abstract mathematical principles connected with complex numbers, with rich and subtle geometrical consequences. If such a view of the ultimate nature of physical reality be correct, then we, like Eddington's "scientific table," are all composed of abstract mathematics!☐

Professor Roger Penrose, one of the world's leading theoretical physicists, holds the Rouse Ball Chair of Mathematics at Oxford University. In 1975 the Royal Astronomical Society awarded him the Eddington Medal jointly with Stephen Hawking, one of several such awards Penrose has received from academic and professional bodies in Britain and America.