

Superstrings

A Theory of Everything?

Edited by

P.C.W. DAVIES

JULIAN BROWN

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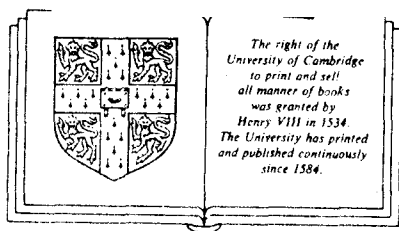
Edited by

P.C.W. DAVIES

Professor of Theoretical Physics, University of Newcastle upon Tyne

JULIAN BROWN

Radio Producer in the BBC Science Unit, London



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PREFACE

In the last few years a remarkable new theory has captured the imagination of physicists. Known as string theory, or in its most developed form as superstring theory, it promises to provide a unified description of all forces, all the fundamental particles of matter, and space and time — in short, a Theory of Everything. The crux of the theory — that the physical world is made out of nothing but little strings — may sound absurd. But the theory is founded upon elegant mathematical ideas whose consequences are proving to be encouragingly consistent with the real world.

Such is the appeal of string theory that it has now become one of the liveliest research disciplines in theoretical physics, and has attracted the attention of many distinguished theorists. Some scientists have become greatly excited by the prospects of the theory, and have made spirited claims for its possible success. Nevertheless, the theory is not without its critics as you will discover by reading this book.

In 1987 we decided to review the state of superstring research by making a documentary on the subject for BBC Radio 3. The programme *Desperately Seeking Superstrings* was broadcast in early 1988. For this we sought the elucidation and opinions of some of the leading proponents and critics of string theory. As in our previous collaboration *The Ghost in the Atom* (Cambridge University Press, 1986) which started life as a radio documentary before metamorphosing into a book, we felt that it would be worthwhile publishing the interviews in a fuller

and more permanent form. We have adhered to the original transcripts as much as possible, but inevitably some alterations were required to render the interviews more suitable for the printed page. We have, however, endeavoured to retain their conversational character.

The intention of this book is to give both physicists and interested non-physicists an insight into the essential ideas of string theory. We also hope that readers will find that the book offers a useful glimpse of how leading physicists talk and argue about a subject of contemporary importance. As the interviews were intended for a general audience, we asked our contributors to talk informally and to avoid using too much technical jargon. Each of the interviews is self-contained, and can be read in isolation. However, to provide a linking framework, we have written an extensive introduction, in which many of the background ideas that are needed for a fuller understanding of the theory are explained. There you will find brief accounts of quantum physics and the theory of relativity, as well as a survey of particle physics.

Although the subject of superstrings is still in a state of rapid development, the essence of the theory is now well established, and we hope that this book will provide a useful and entertaining snapshot of what could turn out to be one of the great scientific advances of our age.

We should like to thank Dr Ian Moss for assistance with the word processing and Miss Aileen Dryburgh for transcribing the audio tapes.

P.C.W. Davies
Julian R. Brown

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Introduction

1.1 What is a Theory of Everything?

No science is more pretentious than physics, for the physicist lays claim to the whole universe as his subject matter. Whereas biologists are restricted to living organisms, chemists to atoms and molecules, psychologists to man and his fellow creatures, and so on, physicists, like theologians, are wont to deny that any system is in principle beyond the scope of their subject.

Physicists, of course, readily concede that in practice their understanding of most systems is woefully limited. Systems as basic as clouds and snowflakes are notoriously hard to model using the familiar laws of physics. As for biological systems, even the most primitive of organisms such as a virus or bacterium defeat the efforts of the physicist by virtue of their overwhelming complexity. Nevertheless, this practical impotence tends to be dismissed on the grounds that however mysterious a complex system may be, its behaviour must ultimately be dictated by the laws of physics, and *nothing* else.

The notion that nothing but the laws of physics are needed to account for the entire universe, in all its infinitely subtle detail, is encouraged by the philosophy of reductionism. Advocates of this school of thought, which includes many scientists, believe that, in principle, psychology can be reduced to biology, biology to chemistry and chemistry to physics. In other words, the 'arrows of explanation' always point downwards to the deepest layer of reality until, ultimately, everything can be explained in terms of the fundamental constituents of matter. The reductionist will therefore assert that if a consistent and

complete theory of these constituents can be elucidated, it will *ipso facto* constitute a Theory of Everything.

We do not intend to argue here whether this reductionist line of reasoning can be sustained, but merely point out that it is in this spirit that some physicists have recently been talking about Theories of Everything, or TOEs. It is important to realize, however, that such a 'Theory of Everything' is not going to *explain* everything, just as in mathematics the axioms of geometry do not really 'explain' Pythagoras' theorem. It is true that Pythagoras' theorem can be deduced from the axioms, but the proof involves a fairly complicated chain of reasoning. The point is that even if we identify the fundamental elements of the physical world, we cannot expect an understanding of its many complex features to follow automatically. Thus the physicists' TOE will not solve many practical problems such as how to model clouds or snowflakes, let alone impinge on such grander mysteries as the origin of life or the nature of consciousness. Yet, according to the reductionist philosophy, an explanation for all of these phenomena should in principle be derivable from the TOE.

The first TOE (as far as we know) was constructed in the fifth century BC by the Greek philosophers Leucippus and Democritus. Their theory was called Atomism, and it asserted that the world consisted of nothing but atoms and the void. There were a number of different types of atoms, but all were supposed to be *elementary*, in the sense of being impenetrable and indestructible. This implied that atoms had no internal parts; they could not be said to be 'made up of' anything smaller. Atoms would have to be too small to observe directly and to be in a state of continual motion through the void. It was further argued that encounters between atoms might cause some to stick to others, producing the impression of continuous matter and that any change in the physical world could be attributed to the rearrangements of these atoms.

Following the rise of modern science with the work of Galileo and Newton in the seventeenth century, the atomic theory was supported by the elucidation of the laws of motion for material bodies. It now became possible to conceive that even the movement of the atoms obeys well-understood

physical laws. This advance inspired Laplace to invent his famous demon calculator:

An intelligence knowing, at any given instant of time, all forces acting in nature, as well as the momentary positions of all things of which the universe consists, would be able to comprehend the motions of the largest bodies of the world and those of the smallest atoms in one single formula, provided it were sufficiently powerful to subject all data to analysis; to it, nothing would be uncertain, both future and past would be present before its eyes.

This surely constituted an attempt at a Theory of Everything.

Some things, however, were conspicuously absent from this would-be TOE. No attempt was made to explain why the universe contains the atoms it does. The question of where they came from and why they have the masses and forms they have was left unanswered. The nature of the forces that act between atoms was also somewhat vague. Newton had provided a theory of gravity, but this was inadequate to account for all interatomic forces. Furthermore, the space through which atoms move, and the time by which their progress is gauged, lay outside the scope of the theory entirely. Space and time were regarded as simply *there*, not themselves part of physics. In these respects, then, the work of Galileo, Newton and Laplace could not be considered to constitute a very satisfactory TOE.

The situation remained largely unchanged until the latter half of the nineteenth century, when Newton's laws of mechanics and gravitation were supplemented with Maxwell's theory of electromagnetism. For a while it was possible to imagine that all natural forces might be a manifestation of either gravitation or electromagnetism in one guise or another. Although there was still no explanation for the existence of atoms, and space and time remained outside physics, many physicists assumed that their job from henceforth merely involved measuring the next decimal place of various physical quantities. In a speech to the British Association for the Advancement of Science in 1900, Lord Kelvin said: 'There is

nothing new to be discovered in physics now. All that remains is more and more precise measurement.' There was thus a feeling abroad that a TOE was at hand.

With the benefit of hindsight we can see that an unsatisfactory feature of any purported TOE at that time was the need to postulate *two* fundamental forces: gravitation and electromagnetism. An attempt to remedy this shortcoming was made in about 1920 by the mathematician Theodor Kaluza, who discovered a possible link between the two forces (discussed in more detail later). Thus a serious candidate for a TOE might have come to prominence much earlier this century had physics not already been caught up in a conceptual maelstrom.

The discoveries of the electron and of radioactivity, the success of Planck's quantum hypothesis and the inception of Einstein's theory of relativity swept away the entire basis of Newtonian—Maxwellian physics. Newton's laws of motion and his commonsense assumptions about space and time were abandoned. Even Democritus' atomic hypothesis had to be replaced by a more subtle and complex view of the microworld in which atoms could no longer be regarded as indestructible particles with a well-defined position and motion. It became apparent that the foundations of classical physics had collapsed.

By about 1930 their place had been taken by new theoretical schemes: *quantum* mechanics, the general theory of relativity and a more elaborate model of the atom. Though many details remained obscure, physics seemed once more to be returning to a relatively simple set of principles. Although what had been called the atom turned out to be a composite body, it was still possible to conceive of all matter being composed entirely from a small number of *elementary* particles (electrons, protons, neutrons), subject to the laws of relativity and quantum mechanics. Indeed, in a mood of unrestrained optimism Eddington published as early as 1923 the beginnings of his so-called fundamental theory, an ambitious attempt at a TOE based on curious numerological relationships. Eddington continued to elaborate such ideas until his death in 1946. Einstein too spent much of his later years searching for a 'unified field theory' based on a purely geometrical description of nature.

But as we now know, all hopes for a TOE based on 1920s physics were premature. The need to postulate neutrinos, the discovery of the positron and the muon, and the clear manifestation of additional forces associated with the atomic nucleus eventually put paid to the idea that the fundamental rules of the universe operate at the level of simple interactions between electrons, neutrons and protons. Experimental *particle physics* flourished, unveiling a plethora of subatomic fragments and a bewildering tangle of forces. Physics proved to be far more complicated than had been suspected in the 20s.

It has taken a further half century for physicists to identify the deeper level of structure that underlies this subatomic richness, and to provide a more or less satisfactory theory of matter and forces. With this new understanding, some physicists have recently felt sufficiently emboldened to raise once more the prospect of a Theory of Everything. Superstring theory is the latest and by far the most promising attempt at a TOE. The regime in which this new confluence of ideas applies is ultra-microscopic. The world of the atom, or experimental high energy particle physics, is fully twenty powers of ten larger than the realm of the superstring.

What should we expect from a truly satisfactory TOE? First, it should explain why physicists observe the various elementary particles that they do, and correctly predict all of their key properties such as mass, electric charge, magnetic moment and so on. Second, it should faithfully describe all the interactions between the particles, which means that it should account for not only the four fundamental forces of nature, but also their relative strengths. Calculations with the theory also ought to yield precisely the observed values of the various inter-particle scattering amplitudes, decay rates, branching ratios, etc. In short, the theory should account for all the measured parameters of particle physics. In addition to this, it should provide an explanation for the geometry and topology of spacetime, such as the number of perceived dimensions, and offer a convincing account of how the universe came into existence.

But this is not all. A TOE should also *unify* physics.

1.2 Unity at the heart of nature

Anybody can have a stab at constructing a TOE. Just go to the textbooks, write down all the basic laws, enumerate all the known subatomic particles and their forces, and display the whole lot. There it is, everything you always needed to know about the universe!

So what is wrong with that approach? The problem is partly aesthetic: such a list looks messy. A good TOE should consist of much more than a mere catalogue of underlying laws and objects; it should have explanatory power, and it should establish *linkages* between the various facets of nature. Admittedly, the search for such a TOE is to a certain extent an act of faith, motivated by the deep belief that nature ought to be simple.

Generally speaking, the fewer the number of independent assumptions in a scientific theory, the more powerful and compelling it is. Theories often retain free parameters which have to be fixed empirically. With further advances, a deeper theory might then provide the values of those parameters. To take a specific example, the Stefan-Boltzmann radiation law of the 1880s related the energy density of black body radiation to the fourth power of the temperature. The constant of proportionality was fixed by experiment. Following Planck's successful quantum hypothesis in 1900, this quantity was shown not to be an independent fundamental constant of nature, but derivable in terms of other constants of physics, viz. the speed of light, Planck's constant and Boltzmann's constant.

Scientific experience has demonstrated many times that the deeper one probes, the more connections become apparent and the less one needs to fix apparently arbitrary aspects of theory by appeal to direct experiment. Thus the modern concept of the atom improves on the classical picture because it shows how different types of atoms arise from the same few constituents of matter. There is no need to postulate ninety or so different fundamental objects, each corresponding to a chemical element. Today, the physical and chemical properties of different atoms can be related systematically in terms of their constituent parts.

The ultimate TOE would, ideally, need no recourse to experiment at all! Everything would be defined in terms of everything else. Only a single undetermined parameter would remain, to define the scale of units with which the elements of the theory are quantified. This alone must be fixed empirically. (In this ultimate case, experiment merely serves to define a measurement convention. It does not determine any parameter in the theory.) Such a theory would be based upon a single principle, a principle from which all of nature flows. This principle would presumably be a succinct mathematical expression that alone embodied all of fundamental physics. In the words of Leon Lederman, director of Fermilab — the giant particle accelerator facility near Chicago — it would be a formula that you could 'wear on your T shirt'.

Attempts to unify physics follow two quite different strategies. The first of these might be called the 'top-down' approach. One starts with some broad, overarching principle, perhaps justified on the grounds of elegance or simplicity and probably expressed in succinct mathematical form. One then works towards a description of the world, arriving only in the last analysis at specific predictions.

Much of Einstein's work exemplified the power of the top-down route. His development of the general theory of relativity was founded on the principle of the equivalence of gravitational and inertial forces, and the principle that physics must be independent of the coordinate system in which events are described. From such basic and elementary ideas Einstein was led almost uniquely to his gravitational field equations. The equations themselves are renowned for their elegance, simplicity and compactness. However, the *solution* of these equations is usually far from simple. Computations of, say, the motions of the planets or the emission of gravitational radiation from binary stars are very complicated. So even after more than sixty years, the full consequences of the theory have yet to be revealed.

In contrast is the 'bottom-up' approach to science which is probably more commonplace. Here one starts out with phenomenology. Laboratory experiments provide a mass of raw data, which is then organized systematically, and certain regularities deduced. These regularities are refined to specific

postulates, leading to laws of greater generality. Predictions are made about phenomena in new areas, and experiments used to test those predictions. Piece by piece, the scientist fashions linkages here and there, and with any luck he eventually assembles a theory that is greater than the sum of its parts. Particle physics provides many examples of the success of this approach. The quark theory, for instance, was arrived at by successive stages of unification of apparently different particles into families, or multiplets, suggested by various physical similarities deduced from experiment. The essence of the bottom-up route is that it never strays too far from the path indicated by experiment, and if the experimental facts lead away from philosophical elegance, so much the worse for philosophy.

The history of physics is the history of successive stages of unification. Newton, for example, demonstrated that the motion of the heavenly bodies conforms to the same dynamical and gravitational laws as bodies near the surface of the Earth. Maxwell unified the laws of electricity and magnetism, and in addition established a link between electromagnetic field theory and optics by showing that light consists of electromagnetic waves. Einstein found a connection between space and time, and energy and mass, and then went on to link spacetime to gravitation.

In recent years attempts to unify nature further have focused upon high energy particle physics. The reason for this is that the deeper the level of structure we want to examine the higher the energy we have to use. In this regime, two theories are paramount. The first is the theory of relativity, the second is quantum theory. A starting assumption of all recent attempts to unify physics is that these two theories must be explicitly incorporated. Before we examine particle physics, then, let us briefly review these two theories.

1.3 The theory of relativity

In the late nineteenth century it became apparent that Newton's laws of mechanics and Maxwell's theory of electrodynamics gave conflicting descriptions of relative motion. According to Galileo and Newton, uniform motion in

a straight line is purely relative to some frame of reference; the motion does not produce any absolute physical effects. Thus in a smoothly flying aircraft the passenger has no real sensation of speed, and can verify his motion only by reference to some external system, e.g. by looking out of the window and seeing the ground go by. On the other hand Maxwell's equations predict that electromagnetic waves such as light travel at a velocity which is a fixed constant for free space. The speed of light is therefore a universal constant of nature. The theory says nothing about the frame of reference against which this speed should be measured. An idea developed that space must be filled with an invisible medium called the *aether* through which light propagates. The aether would then define a universal frame of rest against which all motion could, in principle, be gauged. This it seemed would reconcile Maxwell's theory with the principle of relativity enunciated by Galileo and Newton. However, experiments to determine the speed of the Earth through the aether gave the result zero. This was utterly paradoxical, for it seemed to imply that the Earth was at rest and the heavens in motion about it!

In 1905 Einstein published his so-called special theory of relativity which addressed this paradox directly. Einstein upheld the principle of relativity – that uniform motion in a straight line is purely relative – but rejected the aether. Instead he introduced a new postulate into physics. This states that the speed of light is the same in all reference frames. It implies that, irrespective of the state of motion of the light source or observer, light will pass the observer at exactly the same speed. Two observers in relative motion who observe the *same* light pulse will nevertheless measure the *same* speed for that pulse.

Einstein's new principle of the constancy of the speed of light requires one to discard commonsense notions of space and time. In particular, Newton's treatment of space, time and motion had to be replaced with a new 'relativistic' theory. Central to the relativistic concept of space and time is that spatial distances and intervals of time will be perceived differently by different observers according to their state of motion. In this way an interval of, say, one hour on Earth might be measured as only half an hour in an incredibly fast spacecraft. Similar remarks apply to lengths. These relativistic

effects, however, are very small unless the speeds involved are close to that of light. In high energy particle physics the particles often travel very close to the speed of light and experience very pronounced time dilation. The effect shows up directly in the way in which unstable particles take much longer to decay (as measured at the laboratory bench) when whirling around a particle accelerator than they do at rest.

These distortions of space and time have a profound effect on the laws of mechanics. For example, a moving body is, roughly speaking, heavier than when at rest; its mass rises as it is accelerated. The concept of mass is therefore somewhat ambiguous. Physicists usually define the mass of a body to be its mass as measured when at rest (relative to the observer making the measurement). The effective mass (or relativistic mass) as represented by, say, the body's inertia, depends on its speed, and rises without limit as the speed of light is approached. An examination of the relationship between mass, speed and energy in the theory of relativity reveals that mass and energy are equivalent. The statement means that energy has mass, and that matter is a form of energy. It also implies that, under certain circumstances, matter might be destroyed and replaced by some other form of energy. Conversely, energy might be used to create matter. These ideas are embodied in Einstein's famous equation $E = mc^2$, where E is energy, m is mass and c is the speed of light.

As a consequence of these ideas, it is impossible for a particle, or any other object, to 'break the light barrier'. That is, no particle can accelerate from less than the speed of light to greater than the speed of light. One way to understand this is in terms of mass, for the mass of an object would become infinite at the speed of light and thus require an infinite amount of energy to accelerate it to that state, which is impossible.

The above restriction does not, of course, imply that nothing can travel at the speed of light, for clearly light itself does. For a particle to travel at the speed of light its rest mass must be zero (though not its actual mass, for such a particle can never be at rest). Moreover, the theory of relativity does not specifically exclude the possibility of particles that travel faster than light. Such hypothetical particles have gained the name *tachyons*;

these are forbidden by the theory of relativity from crossing the light barrier the other way, i.e. they can never travel slower than light. According to the equations of relativity a tachyon's rest mass would be an imaginary number (i.e. the square root of a negative number). This would be an embarrassment if the rest mass of tachyons were a measurable quantity, but as they are forbidden from travelling slower than light they could never be brought to rest anyway.

Although tachyons are allowed by the theory, most physicists regard them with distaste. For a start, their faster-than-light motion implies that under some circumstances they could travel backwards in time. If tachyons can interact with ordinary matter, it seems that they could convey messages to the past, thus leading to the possibility of all sorts of awkward causal paradoxes. Some attempts have been made to circumvent this by redefining the direction of time along the paths of such tachyons (i.e. by regarding a tachyon travelling backwards in time from place A to place B as a tachyon travelling forwards in time from B to A) but it is not clear whether this can be done consistently. The idea of tachyons runs into even greater problems when quantum theory is taken into account.

The transformation of space and time intervals predicted by the theory of relativity implies that space and time are part of physics, rather than an arena in which physics takes place. Indeed, the way in which the transformations work reveals that space and time are inextricably linked, and should be regarded as forming a four-dimensional continuum called *spacetime*. For this reason physicists think of the world as four-dimensional rather than three-dimensional.

It soon became clear to Einstein that the special theory of relativity meant abandoning not only the Newtonian concepts of space and time and the laws of mechanics, but also Newton's theory of gravity. According to Newton, gravitational forces act instantaneously across space. But this would violate the theory of relativity because it implies that gravitational effects travel faster than light.

Einstein set out to construct a new theory of gravitation based upon a generalization of his theory of relativity. This took many years; he completed the task in 1915. In the original 'special' theory, Einstein was concerned with uniform motion.