JOHN D. BARROW

New Theories of Everything

THE QUEST FOR ULTIMATE EXPLANATION

'I am very interested in
the Universe—I am specialising
in the Universe and all
that surrounds it'

—PETER COOK

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CHAPTER 1

Ultimate explanation

> I have yet to see any problem, however complicated, which when you looked at it in the right way, did not become still more complicated.
> — POUL ANDERSON

AN EIGHTFOLD WAY

> It seemed to me a superlative thing—to know the explanation of everything, why it comes to be, why it perishes, why it is.
> — SOCRATES

How, when, and why did the Universe come into being? Such ultimate questions have been out of fashion for centuries. Scientists grew wary of them; theologians and philosophers grew weary of them. But suddenly scientists are asking such questions in all seriousness and theologians find their thinking pre-empted and guided by the mathematical speculations of a new generation of scientists. Ironically, few theologians have an adequate training in physics to keep abreast of the details, and few physicists have a sufficient appreciation of the wider questions to make a fruitful dialogue easy. The theologians think they know the questions but cannot understand the answers. The physicists think they know the answers but don't know the questions. An optimist might thus regard a dialogue as a recipe for enlightenment, whilst the pessimist might predict the likely outcome to be a state in which we find ourselves knowing neither the questions nor the answers.

Modern physicists believe they have stumbled upon a key which leads to the mathematical secret at the heart of the Universe—a discovery that points towards a 'Theory of Everything', a single all-embracing picture of all the laws of Nature from which the inevitability of all things seen must follow with unimpeachable logic. With possession of this cosmic Rosetta Stone, we could read the book of Nature in all tenses: we could understand all that was, is, and is to come. Of such a prospect, there has always been speculation but never confidence. But is this confidence now misplaced? This is one of the questions that the reader will be in a position to answer after turning the final page of this book. It is our intention to spell out the different ingredients that must comprise any scientific understanding of the Universe in which we live. These we shall find to be more diverse and slippery than has fondly been imagined by the purveyors of Theories of Everything. Of course, we must be circumspect in our use of such a loaded term as 'Everything'. Does it really mean everything: the works of Shakespeare, the Taj Mahal, the Mona Lisa? No, it doesn't. And the way in which such particulars of the world fit into the general scheme of things we shall discuss at some length in the pages to come. It is a vital distinction that needs to be made in our approach to the study of Nature. For we might like to know if there are things which cannot be straitjacketed into the mathematically determined world of science. We shall see that there are, and we will attempt to explain how they may be distinguished from the codifiable and predictable ingredients of the scientific world that will populate any Theory of Everything.

Scanning the past millennia of human achievement reveals just how much has been achieved during the last three hundred years since Newton set in motion the effective mathematization of Nature. We have found that the world is curiously adapted to a simple mathematical description. It is enigma enough that the world is described by mathematics; but by *simple* mathematics, of the sort that a few years energetic study now produces familiarity with, this is a mystery within an enigma.

Several are the reactions to this state of affairs. We could regard the Newtonian revolution as the discovery of a master key which opens doors faster with constant use. And although the pace of discovery has quickened dramatically in recent times, it will none the less continue to do so indefinitely. Our present pace of discovery of truths about seemingly fundamental things does not necessarily indicate that we are about to converge upon the spot where all the treasure lies buried. The process of discovery could continue indefinitely either because the complexity of Nature is truly bottomless or because we have chosen a particular way of describing Nature which, while being as accurate as we desire, is none the less at best always but an asymptotic approximation that only an infinite number of refinements could make correspond exactly to reality. More pessimistically, our human frame and its eventful evolutionary past may place real limits upon the concepts that we can accommodate. Why should our cognitive processes have tuned themselves to such an extravagant quest as the understanding of the entire Universe? Is it not more likely that the Universe is, in Haldane's words, 'queerer than we can ever know'? Whatever our speculations about our own position in the history of scientific discovery, we surely regard with a Copernican suspicion any idea that our human mental powers should be adequate to handle an understanding of Nature at its ultimate level. Why should it be *us*? None of the sophisticated ideas involved appear to offer any selective advantage to be exploited during the pre-conscious period of our evolution. Alternatively, we might take the optimistic view that our recent sucess is indicative of a golden age of discovery which will near completion during the early years of the next century. Thereafter, fundamental science will be more or less complete. True, there will be things left to discover, but they will be matters of detail, applications of known principles, polishing, elegant reformulation, or metaphysical rumination. Historians of science will look back at this and neighbouring centuries as the time when we discovered the laws of Nature.

We have been this way before. Perhaps there is a psychological desire to bring things to a successful completion as the end of each century approaches. Near the end of the last century, many also felt the work of science to be all but done. The Prussian patent office was closed down in the belief that there were no more inventions to be made. But some work carried out by a junior at another patent office in Berne changed all that and opened up all the vistas of twentieth-century physics.

Can we hope to give ultimate explanations of the Universe? Is there a *Theory of Everything* and what could it tell us? And just what would such a theory actually encompass? By their very nature, scientific investigations do not know their end from their beginning. We cannot tell how much of what at present we might be loath even to call science will need to be included in such an all-embracing picture of the world. Indeed, history teaches some interesting lessons in this respect. Today, physicists accept the atomistic viewpoint that material bodies are at root composed of identical elementary particles, as well supported by evidence. It is taught in every university in the world. Yet, this theory of physics began amongst the early Greeks as a philosophical, or even mystical, religion without any supporting observational evidence whatsoever. Thousands of years would pass before we even had the means to gather this evidence. Atomism began life as a philosophical idea that would fail virtually every contemporary test of what should be regarded as 'scientific'; yet, eventually, it became the cornerstone of physical science. One suspects that there are ideas of a similar groundless status by today's standards that will in the future take their place within the accepted 'scientific' picture of reality.

In the chapters ahead, we shall take a look at this quest for ultimate explanation and inquire a little into its ancient and modern precedents. We shall stress, unlike many other commentators, that, while knowledge of such a Theory of Everything, if it exists, is necessary in order to understand the physical universe we see about us, it is far from sufficient to achieve that goal. Other essential ingredients are required. Without them, our knowledge will always remain incomplete and partial, and our quest for ultimate explanation will remain unfulfilled. We shall see how our understanding of the Universe is influenced by eight essential ingredients:

- laws of Nature,
- initial conditions,
- the identity of forces and particles,
- constants of Nature,
- broken symmetries,
- organizing principles,
- selection biases, and
- categories of thought.

As our story develops, we shall enlarge upon the nature and contribution of these ingredients to the search for ultimate explanation. It is the author's naïve hope that some of the ideas that we shall encounter along the way may be of wider interest than merely as support for a cautious attitude towards the likely scope of any Theory of Everything. But before we begin to follow this eightfold way, let us begin at the beginning and look back at some of the first Theories of Everything and how their motivations have matured into those of the twentieth-century enquirers into the nature of things.

MYTHS

When I was a child, I spake as a child, I understood as a child, I thought as a child: but when I became a man, I put away childish things.
— ST PAUL

If you browse through the ancient mythological accounts of the origin of the world and the situation of its inhabitants, the overwhelming impression one obtains is of having wandered into a Theory of Everything. All around there is completeness, confidence, and certainty. There is a place for everything, and everything is in its proper place. Nothing happens by chance. There are neither gaps nor uncertainties. No room for progress; no room for doubt. All things are interwoven into a tapestry of meaning pulled taut by the cords of certainty. Surely these were the first Theories of Everything.

The term 'myth' has taken upon itself a meaning in everyday English usage that betrays its real content. It is a much maligned word. To call something 'a myth', to label a politician's assurances as 'mythical', is now just the journalese for saying these things are false or unreliable. Alternatively, we may simply bundle up myths with legends, fairy stories, and all manner of other fantastic or imaginative literature. But to do so is to miss a layer of meaning that is crucial for our enquiry. A myth is a story imbued with a meaning. The message it contains transcends the naïve medium of the story and allows the hearer to understand why things are as they are. By studying the myths of a particular culture, we do not learn anything terribly interesting about the origin of the Universe or of mankind in the way that their original hearers did; rather, we appreciate how they define the outer boundaries of the imagination of their authors. They reveal what things they have thought about, how far they have followed them, those things they see as important enough to merit explanation, and the extent to which they regard the world as a unity. Once we start asking what the details of these myths mean we have removed ourselves from the mindset of the original hearers. It is like asking the meaning of *Little Red Riding Hood*. No nursery child would dream of asking such a question: if they did so, they would cease to be a child. Like fairy tales, myths are meaningful at many unconscious levels. Too precise an analysis of their message and meaning would remove this multiplicity of layers and reduce the number of hearers who could be influenced by its messages. Myths do not arise from data or as solutions to practical problems. They emerge as antidotes for mankind's psychological suspicion of smallness and insignificance in the face of things he cannot understand.

Our modern attempts to explain everything within some all-encompassing scientific picture differ in certain subtle respects when compared with ancient speculative explanations. For the ancients, it was breadth alone that was the hallmark of success for their Theories of Everything. For us, it is breadth *and* depth that count. If we claim to explain everything that is found in the world by a system of thought which proposes that the whole Universe came into being one hundred years ago with all its complex components ready-made, but bearing all the features of having already existed for millennia, then we do indeed attain a breadth of 'explanation' but our explanation possesses no depth whatsoever. We can extract no more from our theory save what we put into it. A similar theory to the one just proposed was actually considered in the nineteenth century by Philip Gosse in an attempt to reconcile the conflict over fossil evidence for the Earth's great antiquity and widespread public belief in special creation having occurred only a few thousand years ago. Gosse proposed that the rocks appeared with the pre-aged fossils already present, bearing (false) witness to past generations of evolution. A deep theory, by contrast, is one which is able to provide explanations for a wide range of things with a minimal contribution being made to the conclusion by the number of input assumptions. The depth of a particular consequence could be characterized by the effort expended in performing the shortest chain of logical reasoning from the assumptions to the conclusion: the amount of waste heat that a computer would have to generate in the process of computing the answer from scratch.

The weakness of mythological Theories of Everything played a key role in their structure and evolution. If one has a weak explanation, then it lacks real explanatory power. As a result, each fresh fact that is discovered requires a new ingredient in order to weave it into the pre-existing tapestry. We see this displayed most clearly by the proliferation of deities in most ancient cultures. Each time a short chain of explanations ('Why is it raining?'—'Because the rain-god is crying') ends, it tends to end at a deity. In any attempt at ultimate explanation—whether it be mythological or mathematical—there are psychologically acceptable bottom lines. In most mythological stories, the entry of an overseeing deity marks an acceptable end to the backtrack of 'why' questions. The more arbitrary and disparate one's explanations for the events of Nature, so the more deities one will tend to invent.

At first, myths must have been simple and focused upon a single question. With the passage of time, they became intricate and unwieldy, bound only by the laws of poetic form. A new fantasy, a new god: one by one they can be added to the patchwork. There was no sense of the need for economy in the multiplication of arbitrary causes and explanations. All that mattered was that they fitted together in some plausible way. Today such patterns of explanation are not acceptable. Ultimate explanation no longer means only a story that encompasses everything.

An indiscriminate multiplication of deities creates other problems. It implies a conflict of legislation in the natural world. A picture of universal laws imposed upon the world by a Supreme Being will not easily emerge. Indeed, even when we look at the relatively sophisticated society of the Greek gods, we do not find the notion of an all-powerful cosmic lawgiver very evident. Events are decided by negotiation, deception, or argument, rather than by omnipotent decree. Creation proceeds by committee rather than by fiat. In the end, any appeal to such a moody collection of initial causes leads to the multiplication of *ad hoc* explanations, a spawning of unnecessary complexity that is going to require more of the same to keep it going in the future. There is no plausible route towards simplicity. By interlinking causes, by searching always for unity in the face of superficial diversity, modern scientific explanations prize depth above breadth. A deep and narrow theory can, and often does, graduate to become a deep and broad one. A broad and shallow theory never does.

It is not clear how we should regard the originators of the first mythological Theories of Everything. We tend to assume they were realists and hence at worst foolish, at best wrong, in their description of the world. But although most of their hearers undoubtedly did take such stories literally—indeed many people hold somewhat similar views today—there may well have been others who thought of them only as images of some unreachable truth, or cynics who saw them as useful fables or devices for maintaining the status quo.

Lest we relegate the myth-makers and their objectives to the miasmal mists of the past, we should remind ourselves of the way in which the desire for completeness of explanation continued down the centuries. The most striking example is that of the medievals with their bookish desire to codify and order everything that we know or ever could know of Heaven and Earth. Great systems like the *Summa* of Aquinas or Dante's *Divine Comedy* sought to unify all existing knowledge into a labyrinthine unity. Everything had a place; everything had a meaning. As C. S. Lewis observes, it was altogether a little too stifling:

> The human imagination has seldom had before it an object so sublimely ordered as the medieval cosmos. If it has an aesthetic fault, it is perhaps, for us who have known romanticism, a shade too ordered. For all its vast spaces it might in the end afflict us with a kind of claustrophobia. Is there nowhere any vagueness. No undiscovered by-ways? No twilight? Can we never really get out of doors?

And, just as primitive peoples found that unity and completeness led to a vast and unwieldy patchwork of uneasy alliances in order that everything could find a place, so the medievals' desire to harmonize all knowledge into a Theory of Everything became unmanageably complicated. Where the primitive mind met the challenge of completeness by imaginative invention and was then faced with the problem of fitting all these imaginings together, the medieval mind was fettered by its respect for existing books and authorities. It regarded the inherited written words of the ancient philosophers with the same ultimate authority that modern physicists attach to experimental evidence. But the sheer volume of these written authorities ensured that any unification of their philosophical thinking was a vast enterprise. The twentieth century is not immune to such desires either. We have only to look at the problems that had to be faced over the definition and meaning of mathematics near the turn of the century. The formalists wished to protect mathematics from paradox by making it a closed shop: they defined it to be the sum total of all the logical deductions made using all possible rules of inference from all possible starting assumptions. As we shall see in a later chapter, this attempt to trammel up all possible mathematical consequences proved impossible. The desire for completeness could not be realized even here, in the most formalized and controllable human empire of knowledge. This modern urge for completeness had developed hand-in-hand with the desire for a *unified* picture of the world. Where the ancients were content to create many minor deities, each of whom had a hand in explaining the origins of particular things, but might often be in conflict with one another, the legacy of the great monotheistic religions is the expectation of a single over-arching explanation for the Universe. The unity of the Universe is a deep-rooted expectation. A description of the Universe that was not unified in its mode of description, but fragmented into pieces, would invite our minds to look for a further principle which related them to a single source. Again, we notice that this motivation is essentially religious. There is no logical reason why the Universe should not contain surds or arbitrary elements that do not relate to the rest.

CREATION MYTHS

> It is necessary to recognise that with respect to unity and coherence, mythical explanation carries one much further than scientific explanation. For science does not, as its primary objective, seek a complete and definitive explanation of the Universe . . . It satisfies itself with partial and conditional responses. Whether they be magical, mythical or religious, the other systems of explanation include everything. They are applied to all domains. They answer all questions. They account for the origin, for the present and even for the evolution of the universe.
>
> — FRANÇOIS JACOB

We are so familiar with myths and scientific explanations for everything around us that it is no easy task to place ourselves in the prehistoric mindset that existed before any such abstractions were commonplace. We might think that the alternatives available were simply to rely on reason or sight, or upon faith in some invisible personalities or spirits. But this is a false dichotomy. At such a primitive stage, it is very much an act of faith to seek any parallel between our thoughts and the way things are in the outside world. It is by no means obvious that the great impersonal forces of the natural world are amenable to discussion or explanation, far less to prediction. Indeed, so awesome and devastating are many of their effects that they might more persuasively appear to be an enemy or, worse still, the irrational forces of chaos and darkness.

It is with such scales lifted from our eyes that we should approach the ideas that evolved concerning the origins of the world that we find in the mythology and traditions of every culture. These stories are often exhibited as illustrating the prescience of a few ancients for some favourite modern idea like the creation of the Universe out of nothing or its infinite age; but there should be no serious intent behind such juxtaposition of ancient and modern. It is merely that distorted perspective on the past that finds it to be significant solely where it presages our present thinking.

Ancient cosmology was not scientific. Its *raison d'être* was neither to explain observations nor make predictions. Rather, it was to embroider a tapestry of meaning within which its authors could represent themselves, and with respect to which they could evaluate the status of the unknown and the mysterious. The organization of their local society could be justified and reinforced by making it commensurate with the story of the world's origin and form. The starkness of the contrast between their aims and ours is strikingly captured by Frances Yates:

> The basic difference between the attitude of the magician to the world and the attitude of the scientist towards the world is that the former wants to draw the world into himself, whilst the scientist does just the opposite, he externalizes and impersonalizes the world by a movement of will in an entirely opposite direction.

The primitive belief in order and in the sequence of cause and effect displayed by myths is consistent with the belief that it is necessary to have some reason for the existence of everything—a reason that pays due respect for the natural forces which hold life and death in their hands. If one's view of Nature involves a personification of natural forces, then this search for reason reduces to the attribution of blame. Such generalized assumptions by no means lead to a unique collection of ideas about how the Universe came into being. But if one scans all the known myths concerning the origins of the Universe, they reveal a surprisingly small collection of cosmogonical notions. We find rather rarely, and then somewhat ambiguously, a belief in creation of the world out of nothing, but we find also a belief in the restructuring of the world out of pre-existent chaos. Often it suffices for a story to explain the ordered world which we now see. The notion of explaining some pre-existent state from which the world was fashioned either is not called for or is recognized for the cul-de-sac that it will turn out to be. Occasionally, we find adherence to the notion of a cyclic pattern of history taking its cue from the diurnal and seasonal periodicities of the natural world or, more adventurously, to a world that had no beginning. Elsewhere, we encounter the picturesque idea that the world hatched from a 'cosmic egg' or appeared as the progeny of the embrace of two world-parents. In the same vein, we find a collection of traditions in which the world emerges from some primeval womb or is fished from the primordial waters of chaos by a heroic diver. Finally, there is a mythological pattern which embroiders the theme of some titanic figure engaged in a cataclysmic battle against opposing forces of chaos and darkness. Out of the heroic victory of light over darkness is born our own Cosmos.

All of these formulae for dealing with the existence of the world are happy to establish some initial cause beyond which explanations will not be sought. The cause is simple in that it is singular, whereas the world of experience is bewilderingly plural. These fantastic speculations differ from any modern scientific approach to the origin of things because they look to an ultimate purpose as part of the motivation or the initial mode of creation. Yet they share one aspect with modern attempts to understand the Universe. All begin as attempts to explain everything we see about us and find this quest leads inexorably back to the ultimate question: how did the Universe originate? Today, the real goal of the search for a Theory of Everything is not just to understand the structure of all the forms of matter that we find around us but to understand why there is any matter at all, to attempt to show that both the existence and the particular structure of the physical Universe can be understood, to discover whether, in Einstein's words, 'God could have made the Universe in a different way; that is, whether the necessity of logical simplicity leaves any freedom at all'.

ALGORITHMIC COMPRESSIBILITY

Irrationality is the square root of all evil.
— DOUGLAS HOFSTADTER

The goal of science is to make sense of the diversity of Nature. It is not based upon observation alone. It employs observation to gather information about the world and to test predictions about how the world will react to new circumstances, but in between these two procedures lies the heart of the scientific process. This is nothing more than the transformation of lists of observational data into abbreviated form by the recognition of patterns. The recognition of such a pattern allows the information content of the observed sequence of events to be replaced by a shorthand formula which possesses the same, or almost the same, information content. As the scientific method has matured, so we have become aware of more sophisticated types of pattern, new forms of symmetry and new types of algorithm that can miraculously condense vast arrays of observational data into compact formulae. Newton discovered that all the information he could possibly record about the motion of bodies in the heavens or on Earth could be encapsulated in the simple rules that he called the 'three laws of motion' together with his law of gravitation.

We can extend this image of science in a manner that sharpens its focus. Suppose we are presented with any string of symbols. They do not have to be numbers but let us assume for the sake of illustration that they are. We say that the string is 'random' if there is no other representation of the string which is shorter than itself. But we will say that it is 'non-random' if there does exist such an abbreviated representation. So, for example, if we take the string of numbers 2, 4, 6, 8, . . . , and so on *ad infinitum*, then we can represent it more succinctly by recognizing it to be just the list of positive even numbers. It is clearly non-random. A short computer program could instruct the machine to generate the entire infinite sequence.

In general, the shorter the possible representation of a string of numbers, the less random it is. If there is no abbreviated representation at all, then the string is random in the real sense that it contains no discernible order that can be exploited to code its information content more concisely. It has no representation short of a full listing of itself. Any string of symbols that can be given an abbreviated representation is called *algorithmically compressible*.

On this view, we recognize science to be the search for algorithmic compressions. We list sequences of observed data. We try to formulate algorithms that compactly represent the information content of those sequences. Then we test the correctness of our hypothetical abbreviations by using them to predict the next terms in the string. These predictions can then be compared with the future direction of the data sequence. Without the development of algorithmic compressions of data all science would be replaced by mindless stamp collecting—the indiscriminate accumulation of every available fact. Science is predicated upon the belief that the Universe is algorithmically compressible and the modern search for a Theory of Everything is the ultimate expression of that belief, a belief that there is an abbreviated representation of the logic behind the Universe's properties that can be written down in finite form by human beings.

This reflection on the compressibility of Nature also nudges us towards an understanding of why mathematics is so useful in practice. Our scientific theories always seemed to be described by mathematics, and physicists seem only interested in Theories of Everything that are couched in the language of mathematics. Is this telling us something profound about the nature of the Universe or the nature of mathematics? It is simplest to think of mathematics simply as the catalogue of all possible patterns. Some of those patterns are especially attractive and are used for decorative purposes, others are patterns in time or in chains of cause and effect. Some are described solely in abstract terms, while others are made manifest on paper or in stone. When viewed in this way, it is inevitable that the world is described by mathematics. We could not exist in a universe in which there was no pattern or order of any sort. Some order is inevitable for us, and the description of that order (and all the other sorts that we can imagine) is what we call mathematics. So, the fact that mathematics describes the world is not a mystery, but the exceptional utility of mathematics is. It could have been that the patterns behind the world were of exceptional complexity which allowed no algorithms to be developed which approximated them in simple ways. Such a universe would 'be' mathematical but we would not find mathematics terribly useful in practice. We could prove all sorts of 'existence' theorems about what structures exist but we would not be able to predict the future in detail using mathematics in the way that mission control at NASA does. Seeing it in this light, we recognize that the great mystery about mathematics and the world is that such simple mathematics is so far-reaching. Very simple patterns, described by mathematics that is easily within our grasp, allow us to explain and understand a huge part of the Universe and the happenings within it. This is another way of saying that the Universe is extremely compressible in the algorithmic sense. An awful lot of its observed complexity can be reduced to the presence of very simple patterns, described by short formulae and small equations. In many ways the search for a Theory of Everything is a manifestation of a faith that this compression goes all the way down to the bedrock of reality, that the ultimate patterns that give the Universe its shape and feel will also be 'simple' in the sense that we can understand them and discover them. It relies on the complexity of our minds, and the reach of our technologies, being sufficient to understand and find those ultimate patterns. All things being equal, the most likely state of affairs would be that our capabilities are vastly more or vastly less than those required for the task. A situation in which we are *just* able to understand the ultimate patterns behind the Universe using contemporary mathematics has a suspiciously un-Copernican element to it—why are *we* so closely matched in complexity to the Universe.

The human mind is the device that allows us to abbreviate the information content of reality in this way. The brain is the most effective algorithmic compressor of information that we have so far encountered in Nature. It reduces complex sequences of sense data to simple abbreviated forms which permit the existence of thought and memory. The natural limits that nature imposes upon the sensitivity of our eyes and ears prevents us from being overloaded with information about the world. They ensure that the brain receives a manageable amount of information when we look at a picture. If we could see everything down to sub-atomic scales then the information-processing capacity of our brains would need to be prohibitively large. The processing speed would need to be far larger than it now is in order for bodily responses to occur quickly enough to evade dangerous natural processes. This we shall have more to say about in the final chapter of our story, when we come to discuss the mathematical aspects of our mental processing.

This simple picture of the process of scientific enquiry as the search for algorithmic compressions is a compelling one, but it is also a naïve one in many ways. In the chapters to follow, we shall see why this is so and explore the eight ingredients which we have already highlighted as being necessary for our understanding of the physical world, to show what role each plays in the modern quest for an all-encompassing picture of the world. We shall start with the oldest notion: that of the laws of Nature.