Exploring Reality

The Intertwining of Science and Religion

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Preface

After twenty-five years working as a theoretical physicist, I decided that the time had come to do something else, so I turned my collar round and became an Anglican priest. For the past twenty years I have been a scientist-theologian, seeking to combine the perspectives of science and Christianity into a stereoscopic world view.

I have always wanted to make it clear that I did not leave physics because of any disillusionment with that subject. I retain a lively interest in science and a deep respect for all that it can tell us. Yet its enthralling account is not sufficient by itself to quench our thirst for understanding, for science describes only one dimension of the many-layered reality within which we live, restricting itself to the impersonal and general, and bracketing out the personal and unique. Many things altered in my life when I changed from being a physicist and became a priest, but one significant thing remained the same: the central importance of the search for truth. All my life I have been trying to explore reality. That exploration includes science, but it also necessarily takes me beyond it.

The process of investigation has a spiral character, as tackling the issues draws the explorer inwards to a deeper engagement with the multidimensional character of reality. This book reports the most recent cycle of my own exploratory thinking, presenting the latest communiqué from a continuing survey of the frontier between science and religion. Some of its themes are ones that I have visited before, but this compact volume aims to offer additional insight and I have refrained from undue repetition of what I have written already elsewhere. In consequence, there are some issues concerning which I am content simply to offer references to previous writings for the sake of a reader who wishes to follow up these points. Yet I believe that what is presented here is sufficiently self-contained for the volume to be read satisfactorily on its own. I suppose that the kind of iterative approach, pursued here and elsewhere in my work, is a pattern I inherited from all those years as an elementary particle physicist. In that subject, one progressed step by step, slowly building on what had gone before and concentrating at any one time on the pressing problems at hand.

I hope that this progress report will be of some help to others engaged in the great human quest for unified understanding. Because reality is multilayered, its exploration calls for a corresponding multiplicity of levels of enquiry. Account must be taken of what science, in its impersonal way, can tell us about the structure and process of the world, including a recognition that even within its own domain science cannot yet tell a fully integrated story. To this must be added due recognition of the dimension of the personal, acknowledging both the remarkable character of human nature and also the significance of its evolutionary origin. Unique resources for gaining deeper insight are offered to us by the lives and teaching of remarkable individuals. I am particularly concerned with the significance of Jesus of Nazareth. Testimony to meeting with the sacred reality of God, fostered and preserved within a faith tradition, is a dimension of human experience that must be taken with the utmost seriousness. For me as a Christian, this implies exploration of a trinitarian understanding of the divine nature. The first five chapters of the book cover this ground in a sequence with an intensifying focus, moving from the generality of science to the uniqueness of the one true God.

The remaining five chapters are concerned with issues that cluster round that opening progression. Human experience of time is fundamental to our encounter with reality, yet perplexing in its character. Honest recognition of the diversity of human religious perspectives, and admission of the apparent ambiguity of a world that is both beautiful and bitter in its nature, must both be part of engaging with reality as we actually encounter it. The moral dimension of human life, including contemporary perplexities that arise from seeking to apply ethical principles in novel and unprecedented situations, presents challenges to society in its search for right decisions and just procedures. All these issues have to be addressed.

The opening chapter is a very brief explanation of how natural the task of exploring reality is for someone whose intellectual formation has been in the sciences, notwithstanding the raised eyebrows of some postmodernist colleagues about any notion of access to the way things actually are. I nail my colours to the mast and assert my belief in critical realism. On this occasion, however, I do not seek to lay out the detailed defence that this philosophical stance undoubtedly requires, since I have written pretty extensively on this topic in other books of mine.

Chapter 2 surveys current understanding of the causal structure of the world. It centres on two main themes. One is that scientifically our knowledge is still pretty patchy, excellent within certain well-defined domains but often unable to make satisfactory connections between different domains. The problematic of the relationship of quantum physics to classical physics provides an instructive example. The second theme is that matters of causality, though certainly influenced by scientific discoveries, are not finally settled by science alone. Ultimate conclusions have to rest on the foundation of a metaphysical decision. Quantum theory, and chaos theory, and the issue of the relationship between them, all provide illustrative examples of this fact. This is the chapter that will make the greatest demands on the reader without much of a scientific background, but I have tried not to use ideas without offering a non-technical explanation of them. I believe that it is worth putting in some effort to be able to appreciate how the scientific account of causal structure, though deeply insightful, is still far from being complete.

Chapter 3 acknowledges the permanent power of the contribution made by evolutionary thinking to our understanding of the nature of reality. However, the success of evolutionary explanation requires an adequate characterisation of the environmental context within which the processes take place, as well as an understanding of the processes themselves. This kind of thinking depends for its success as much upon getting the ecology right as on getting the genetic factors right. Recognition of the remarkable richness of human experience, and of the unique abilities possessed by the genus *Homo*, persuades me that a simple neo-Darwinian account, based only on differential gene selection within an environment described solely in physico-biological terms, is inadequate to the task of understanding humanity. Human nature should certainly be considered in an evolutionary context, but this requires acknowledgement of the metaphysically rich setting in which that development has taken place. Noetic dimensions of reality, such as those of the mathematical and the moral, are as significant to the human story as are the dimensions of materiality. Human beings are psychosomatic unities living in a world whose understanding requires that a proper balance be struck between the mental and the material, an equal-handedness of the kind to which a philosophy of dual-aspect monism aspires. Human beings are also creatures who live in the veiled presence of their Creator. No account of human nature will be adequate that does not take the dimension of the sacred seriously. This requires an unfashionable acknowledgement of human heteronomy before God.

Chapter 4 turns from the generality of what has gone before to consideration of the astonishing influence of a specific individual. Jesus of Nazareth lived two thousand years ago in a peripheral province of the Roman Empire. He died a painful and shameful death, deserted by his followers and leaving no personally written account of himself or his ideas. On the face of it, it seems a story of initial promise ending in dismal failure. Yet Jesus has been one of the most influential figures in world history. This chapter approaches his life from the point of view of a careful historical evaluation of what can be learned about him from the gospel material. My conclusion, however, is that an adequate explanation of why the story of Jesus continued beyond the apparently miserable end of his crucifixion forces the enquirer to be prepared to go beyond the limited possibilities of an historical naturalism, predicated on the belief that what usually happens is what always happens. The chapter indicates the evidential motivations that point to taking seriously the claim of the truth of Jesus' resurrection, but it acknowledges that the way this evidence is weighed must depend upon theological judgements that go beyond the verdicts of purely secular history. My principal purpose in this chapter is to demonstrate that the question of Jesus is an indispensable item on the agenda for the exploration of reality, but I do not repeat the full defence of an orthodox Christian assessment of his significance that I have given already in my Gifford Lectures.

Chapter 5 turns instead to a topic on which I have written only sparingly before, trinitarian theology. Emphasis is laid on the manner in which trinitarian thinking arose as a response to Christian experience, both that recorded in scripture and that continued in the worshipping life of the Church, rather than from any unbridled indulgence in rash speculation about the ineffable nature of God. In recent years there has been a considerable revival of interest in the theological fruitfulness of trinitarian thinking. Much of the motivation for this has come from an enhanced recognition of the fundamental significance of relationality, a development that can draw some support from aspects of modern science. This is the chapter that will make the most demands on a reader without much of a theological background but, as in the case of science in chapter 2, I endeavour to explain the main concepts to which I refer.

Time remains a continuing topic for metaphysical discussion and dispute. Chapter 6 defends an unfolding and developmental view of temporality against the atemporal claims of the proponents of the block universe. The stance adopted carries with it implications for the Creator's relationship to the time of creation and for the character of divine omniscience. I also suggest that it encourages a developmental view of scripture, seen as the record of an evolving divine revelation conditioned at all stages by the contingencies of history.

One of the most perplexing problems for someone seeking to explore divine reality arises from the conflicting testimonies of the world faith traditions. While I write from within the Christian tradition, I cannot do so unaware of the different insights and understandings of my brothers and sisters in other religious communities. Chapter 7 acknowledges that the ecumenical encounter of the world religions must take place on the basis of recognising both the clashing diversity and the spiritual authenticity that are present in what the traditions have to say. I do not have much new to say on this important topic beyond emphasising that, from a Christian perspective, it is belief in the veiled working of the Spirit that provides the theological basis for undertaking what will undoubtedly prove to be a long and difficult dialogue.

Chapter 8 considers the perplexing challenge to theism presented by the existence of evil and suffering. It suggests that the free-will defence offers some insight into the presence of moral evil, and an analogous free-process defence into the presence of natural evil. It is acknowledged, however, that the challenge of evil cannot be met solely at the level of philosophical argument. The deepest Christian response lies in recognising the passion of Christ as being divine participation in the travail of creation, so that the crucified God is truly a fellow sufferer who understands.

Ethical issues cannot simply be treated in broad generality, for many of the greatest challenges that we face come from very specific problems and perplexities. During the past fifteen years I have had the privilege of serving on several committees charged with offering advice to the United Kingdom Government about ethical issues that have arisen from scientific and technological advances, particularly in the field of genetics. In chapter 9 I seek to use this experience as a resource for exploring the complex nature of debate about the nature of ethical reality. The chapter looks at some of the current moral questions related to embryonic stem cells and other new genetic developments. Evaluation of feasibility by the relevant specialists is an essential input, but the possibilities have then to be assessed within a broader context of responsibility. The voices of the experts and of representatives of the ethically concerned public must both be given an adequate hearing. As a consequence, discussion has to be temperate and interdisciplinary if the technological power afforded by scientific advance is to be used in ethically justified ways that succeed in accepting the good but refusing the bad.

The book ends with chapter 10, a short speculative excursus in which I allow myself imaginative liberty to explore certain aspects of the eschatological hope of a destiny beyond death. The aim is modest: the exploration of some conceptual possibilities, rather than the certain establishment of the details of the life of heaven. I see the discussion as analogous to the use of 'thought experiments' in science.

CHAPTER ONE

Reality?

FOR some the title of this book will be a red rag to a bull. They will dismiss it as exhibiting the author's naivety. 'Reality', and the closely-allied word 'truth', are not in common currency in some circles today, and consequently those who employ them lay themselves open to intellectual condescension and pity. I am unrepentant.

Much of the tone of contemporary sceptical discourse was already set by those nineteenth-century Masters of Suspicion, Friedrich Nietzsche and Sigmund Freud. The former once referred to truths as illusions that we have forgotten are illusions, and the latter, through his work in human psychology, suggested that the actual motivations for our beliefs often lie hidden in unconscious depths, so that they are frequently quite different from those which our conscious egos propose to us. Of course, each of these thinkers implicitly exempted their own ideas from subversion along the lines of their particular critiques, as also did Karl Marx in relation to the influence of economic factors and social class.

More recently, the extreme wing of the movement loosely categorised as postmodernism has suggested that instead of truth about reality, we have to settle for a portfolio of opinions expressing personal or societal points of view. Though there may appear to be conflicts between the different perspectives proposed, it is said that there is no real competition because, in fact, there is not actually anything to contend about. All points of view can claim equal authenticity, since none is constrained by an independently accessible external reality. The story goes that intellectual life is strictly à la carte.

Science has not been exempt from this assault on the possibility of rationally conclusive discourse. Its findings are held simply to be the products of the communities that propose them; its theorisings are supposed to be more about the exercise of power than about the attainment of veracity. For the extreme postmodernist, there are not really quarks and gluons as the constituents of matter, but the idea of them is a construct of the invisible college of physicists, who have simply colluded in seeing the world in a quarklike way.

As with many other reductive and dismissive accounts of human activity and human nature, these critiques are based at best on no more than quarter truths, whose scope is then exaggerated in the attempt to promote them into the pretension of total explanation. Of course, the motivations for human beliefs do lie at a variety of levels within the psyche, an insight known to Augustine and to generations of spiritual directors. Of course, scientific activity is influenced by cultural and social judgements of what investigations it would be valuable to pursue and viable to fund. Of course, experience has to be interpreted before it becomes truly interesting, and this introduces the danger of distortion through tricks of perspective, a problem that has to be recognised and taken into account. A naive objectivity of unproblematic 'facts' is far too crude a way to encapsulate our encounter with the way things are. Yet few critics of the ideas of truth and reality are so committed to that cause that it is matter of indifference to them what kind of doctor, witch or medical, they consult when they are ill. Nor do they tend to regard belief in the safe functioning of the aircraft they are about to board as being sufficiently established if it has arisen simply as the result of a socially negotiated consensus. At the beginning of the twentieth century, the positivist philosopher-physicist Ernst Mach denied the existence of atoms. Can any one really believe today that matter does not have an atomised structure? Scientific knowledge of a reliable kind really does increase. Of course, we know now that atoms themselves are made out of still smaller constituents (quarks, gluons and electrons). The maps that science makes of the physical world have always had to be open to revision when territory comes to be surveyed on a more intimate scale than had been explored hitherto. Yet these maps have proved reliable and trustworthy at the level of detail that they profess to describe. Science's achievement is not absolute truth, but it can rightly claim verisimilitude.

The realist counter-claim that is being made against the sceptics—a claim that certainly requires detailed defence—is that of a *critical realism.* The adjective is necessary because something more subtle than naive objectivity is involved (we do not see quarks directly, but their existence is indirectly inferred). The noun is justified because the best explanation of persistent scientific explanatory power and technological success is that science succeeds in describing, within the acknowledged limits of verisimilitude, the way things actually are.

Almost all scientists, consciously or unconsciously, are critical realists. Scientist-theologians are often self-confessed critical realists about both science and theology.[1] I have written rather often on the subject, seeking to base the argument on case studies, since I do not believe that it can be settled solely by abstract considerations.[2] I do not intend to repeat that discussion here. Let me be content to make three simple points:

(1) Defence of realism in science depends partly upon recognising the unexpected character often stubbornly displayed by nature. Far from its behaving like epistemological clay in our pattern-seeking hands, capable of being moulded into any pleasing shape that takes the fancy, the physical world frequently proves highly surprising, resisting our expectations and forcing us to extend, in unanticipated ways, the range of our intellectual understanding. In consequence, the feel of actually doing science is undeniably one of discovery, rather than pleasing construction. Theologians can claim something similar about the encounter with God. Time and again human pictures of deity prove to be idols that are shattered under the impact of divine reality.

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1. For examples, see I. G. Barbour, *Myths, Models and Paradigms*, SCM Press, 1974; *Religion and Science*, SCM Press, 1998, ch. 5; A. R. Peacocke, *Intimations of Reality*, University of Notre Dame Press, 1984; *Theology for a Scientific Age*, SCM Press, 1993, pp. 7–23; and note 2.

2. J. C. Polkinghorne, *One World*, SPCK/Princeton University Press, 1986, chs 1–3; *Reason and Reality*, SPCK/Trinity Press International, 1991, chs 1 and 2; *Science and Christian Belief/The Faith of a Physicist*, SPCK/Fortress, 1994/1996, ch. 2; *Beyond Science*, Cambridge University Press, 1996, ch. 2; *Belief in God in an Age of Science*, Yale University Press, 1998, chs 2 and 5; *Faith, Science and Understanding*, SPCK/Yale University Press, 2000, chs 2, 3 and 5. 1.

(2) An experience fundamental to the pursuit of science is a sense of wonder, induced by the beautiful order and fruitful nature of the universe. There is an authenticity about science's discoveries of explanatory insight that is deeply persuasive that the scientists are 'onto something', gaining knowledge that comes from an external reality and which cannot be conceived as being simply an internally spun fable. Albert Einstein used often to express his awe at the order of nature, saying that he felt a mere child in the presence of the elders when confronted by such intellectual beauty. From deep simplicity comes immense complexity. For example, the genetic code, lying at the basis of all terrestrial life, depends upon certain chemical properties of the nucleotides forming DNA and RNA, which properties are themselves consequences of the outworking of the laws of electromagnetism and quantum theory. In a suitably compact notation, I could literally write the latter on the back of an envelope. No human ingenuity could be believed to be capable of constructing independently a story of such astonishing economy and fruitfulness. Its discovery required the genuine nudge of nature. The religious believer can find here grounds for understanding the universe as a creation, whose deep order and inherent fertility express the mind and will of its Creator.

(3) If interpreted experience is to be the basis of our understanding reality, then our concept of the nature of reality must be sufficiently extensive to be able to accommodate the richness of our experience. The many-levelled character of human encounter with the world resists all attempts to reduce it to a narrow account. In chapter 3 I shall discuss the context within which human life has evolved and is now lived and I shall argue that a just discussion requires recognition not only

of the physico-biological environment, but also of the realms of truth, beauty and goodness. There is an authenticity and richness in human life that demands that we take all of our experience with the utmost seriousness, respecting the multi-dimensional way in which it presents itself to us.

Any metaphysical world view that did not seek to take reality on reality's terms in the way that I have briefly sketched would be unacceptable. I want to use this short book to suggest some thoughts that arise from using trinitarian theology as a way of engaging with reality in the richness and variety of its actual impact upon us, resisting the temptation to embrace prematurely tidy schemes produced by those false reductions which, though they may sound speciously plausible in the abstraction of the study, deny the full authenticity of actual human experience, lived in the world.

CHAPTER TWO

The Causal Nexus of the World

SCIENCE achieves such frequent success in the many areas of its enquiry that it is difficult for us to remember how diverse are those areas and, in many ways, how little understood are the connections between them. Most scientists necessarily spend much of their time concentrating on their own specialised disciplines. Consequently, they seldom raise their eyes to look at the broader scene. Were they to do so, they would behold a fragmented picture, a patchwork of areas of insight only loosely, if at all, connected to each other.

One way of dividing up the scientific account is to introduce a hierarchy of forms of rational enquiry, ordered according to an ascending scale of the complexity of the entities under discussion. Proceeding in this way yields the canonical sequence: physics, chemistry, molecular biology, cellular biology, biology of organisms, neuroscience, psychology, anthropology, sociology.[1] Sub-sequences are readily identified within these levels of description. For example, in the case of physics there is a spectrum of internal complexity running from elementary particle physics to theories of condensed matter and continuum mechanics. The levels overlap to some degree (superconductors are surely more complicated than simple inorganic molecules, so physics and chemistry are not cleanly separated from each other) and the relationship between successive scientific levels can sometimes be a matter of uncertainty and dispute. While all would acknowledge that biochemistry throws very significant light on processes taking place within living entities, the complex character of even a single cell is such that it is by no means clear that a constituent account tells us all that we shall ever need to know about the richly complicated and integrated character of living entities. Francis Crick proclaimed that 'The ultimate aim of the modern movement in biology is in fact to explain *all* biology in terms of physics and chemistry',[2] but whether this ambitious programme is feasible or well conceived is open to very serious question.

Those who think like Crick are strong reductionists. For them, science's technique of splitting entities into constituent parts is not simply a convenient methodological strategy for tackling certain problems, but it also corresponds to the ontological character of nature itself. In their opinion, the constituent picture is simply the fundamental way things are, so

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[1] For more detailed hierarchical analyses, see A. R. Peacocke, *Theology for a Scientific Age*, SCM Press, 1993, pp. 212–48; N. Murphy and G. F. R. Ellis, *The Moral Nature of the Universe*, Fortress, 1996, ch. 2.

[2] F. Crick, *Of Molecules and Men*, University of Washington Press, 1966, p. 10.

that the true account of reality lies solely at the lowest level, with the other levels in the hierarchy of complexity being just complex corollaries of what lies beneath. Logically this should lead these reductionists to accord the palm to elementary particle physics, and there are certainly some people in my old subject who are bombastic enough to entitle its still-unfulfilled quest for a Grand Unified Theory, the search for a 'Theory of Everything'. Yet strong reductionists often display a reluctance to sink below the level of their own discipline, so that geneticists want to attach special significance to genes,[3] and molecular biologists to molecules.[4]

Against the strong reductionists are the emergentists, whose slogan is 'More is different'. For them the whole exceeds the sum of its parts, so that it would be absurdly inappropriate to call a constituent account a Theory of Everything. They point to the degree of conceptual independence that exists between the various levels of the hierarchy of sciences. It is clear that the fitness of an organism for survival in an ecological setting is not an idea that can usefully be transcribed into statements about collections of quarks, gluons and electrons. The critical question remains, however, How different is more? Is it simply that the novel properties manifested by complex entities require an extended range of concepts for their effective description, or is it the case that emergence is even more interesting than that, in that what is involved requires an enhanced understanding of the causal variety of the world?

The point at issue can be illustrated by considering the wetness of water. This is not a property possessed by a single

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[3] R. Dawkins, *The Selfish Gene*, Oxford University Press, 1976.

[4] F. Crick, *The Astonishing Hypothesis*, Simon and Schuster, 1994.

specimen of H_2O, but it is an emergent effect due to the readjustments of the distribution of energy brought about by bringing together a very large aggregation of water molecules. Rather than attempting the impossible task of calculating the mutual interactions of, say, more than 10^{20} molecules, it is convenient to introduce the notion of surface tension in order to think about the behaviour of drops of water. Yet we have every reason to believe that surface tension is simply the macroscopic expression of the consequences of all those microscopic molecular interactions. No causal property of a novel kind is thought to be at work beyond the cumulative effect of intermolecular forces. This kind of phenomenon can be thought of as being *weak emergence*. Metaphysically it is an unproblematic idea, however difficult it may be to unravel scientifically the detail of particular instances.

Strong emergence would correspond to the case in which a new causal principle becomes active in a complex system, of a distinct kind not encountered at lower levels of complexity. More would then be different in a radical way. An example of strong emergence would be if it is indeed the case that human persons possess the power of free agency and are able to act in the world to bring about their choices in a fashion that is not simply an immensely complicated addition of the causal properties of the elementary particles that make up their bodies.

(The question of what degree of freedom humans enjoy in the exercise of agency has, of course, been a matter of long-standing philosophical controversy. Strong emergence would correspond to the so-called liberty of indifference, in which a person makes a choice between genuinely open possibilities, rather than to the liberty of spontaneity, in which actions accord with wishes, but both deed and desire could together be subject to an all-encompassing determination arising from the lowest physical level. The point at issue concerns the status of what philosophers call an incompatibilist account of human freedom, the claim that true personal liberty cannot be reconciled with total physical determinism in the behaviour of constituents. I must confess to being an incompatibilist.)

Is strong emergence of this irreducible kind a conceivable possibility, given what science can tell us about the causal nexus of the world? If the scientific account presented us with a single causal web of known and determinating character, smoothly interpolating between the behaviour of entities encountered at all levels of scientific enquiry but deriving solely from the properties of basic constituents, then the answer would seem to be No. Causality certainly looks like a zero-sum game, and if the causes operating at one level are totally adequate to determine all that happens, the reduction to that level, though doubtless practically infeasible, would surely be ontologically correct. (That is why I am an incompatibilist.) However, the patchwork character of scientific understanding implies that it is by no means certain that such a seamless web of basic causality is the right way to think about science's account of the process of the world. The point can be illustrated from within physics itself before going on to consider the matter in greater generality.

There are two broad types of physical theory employed with great empirical success. One is classical physics, founded on the ideas of Isaac Newton and only somewhat modified in their character by Albert Einstein's great discoveries of special and general relativity. Its picture of the physical world is clear and deterministic. The mathematical expression of classical physics is in terms of differential equations that specify precisely how directly observable physical quantities, such as position and momentum, will vary with time. According to Newtonian thinking, these quantities are believed to be measurable to arbitrary degrees of accuracy and, in principle, they would be completely determined for all time once their initial values were known exactly. Such variables may constitute a discrete set, as in the case of individual particles, or they may carry continuous labels, as in the case of fields spread out through space. The mathematical difference between these two classes simply corresponds to whether the relevant equations are ordinary or partial differential equations. Either type of equation yields a unique solution given a precise and well-posed set of initial conditions. This mathematical property was the source of the conviction, widely held for more than two centuries following the publication of Newton's *Principia*, that the physical world is mechanical, that is to say, tame, controllable and reliably predictable in its behaviour. We shall see that the actual story is more interesting and problematic than that.

The other type of physical theory is quantum physics, brought to a fully developed expression through the great discoveries of the mid-1920s.[5] Its character is quite different from that of classical physics. For one thing, Heisenberg's uncertainty principle asserts that it is impossible to know with arbitrary accuracy both the position and the momentum of a particle. The clear knowledge of initial circumstances assumed by classical physics is in fact unattainable, for the physical world described by quantum theory is intrinsically fuzzy. The scale

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[5] For an account of quantum ideas, see J. C. Polkinghorne, *Quantum Theory: A Very Short Introduction*, Oxford University Press, 2002.

of irreducible uncertainty is set by Planck's constant (denoted by $\hbar$), a fundamental constant of nature whose value is extremely small in terms of everyday magnitudes. This smallness of $\hbar$ is the reason why quantum physics remained undetected until physicists began to probe phenomena at the level of atomic size or smaller.

People commonly say that quantum theory is different from classical physics because it is indeterministic and it deals with probabilities rather than with certainties. The second half of this statement is true (in most cases quantum physics cannot offer precise predictions), but the first half is not necessarily correct. Probabilities can arise in physics for two quite distinct reasons. One is intrinsic indeterminism; the other is ignorance of all the relevant detail of circumstances. The paradigm case of the latter is the fall of a die, where uncertainty of outcome arises from its dependence on the unknown fine detail of the shaking process, rather than from the caprice of absolute chance. It turns out that the probabilistic character of quantum physics could be interpreted as originating in either of these two ways. The great majority of physicists follow Niels Bohr in considering quantum probability to be an intrinsic property, so that Heisenberg's uncertainty principle is understood to be a principle of real indeterminacy. Yet there is an alternative interpretation, due to David Bohm,[6] in which the underlying dynamics is totally deterministic but the actual outcome depends upon certain factors (called 'hidden variables') to which it is impossible for the experimentalists to gain precise epistemic access. According to this view, the uncertainty principle is simply a principle of unavoidable igno-

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[6] See D. Bohm and B. J. Hiley, *The Undivided Universe*, Routledge, 1993.

rance; its significance is epistemological rather than ontological. Bohm's theory has only minority support in the physics community, but the choice between him and Bohr cannot be made on empirical grounds, since the two interpretations give identical experimental predictions. The decision, therefore, has to be made for reasons lying outside of empirical science itself. The majority are not simply following the tradition of the tribe in making their choice, but they appeal to considerations such as economy, elegance and lack of contrivance as being features in support of their judgement. The role of criteria of this kind in reaching a decision shows very clearly that questions relating to causality cannot be settled on strictly scientific grounds alone, but they call for acts of metaphysical assessment. This is a theme to which we shall return.

The pioneers of quantum theory immediately faced the problem of how this new physics was related to the classical physics which had proved splendidly successful in so many experimentally sifted domains. Two rather different lines of approach were followed. One was taken by Niels Bohr. He had made very significant contributions to the pioneering but piecemeal developments of early quantum thinking but, by the time a fully articulated theory had come to light through the discoveries of Werner Heisenberg and Erwin Schroedinger, Bohr had moved on to the grandfatherly role of being the philosophical guru of the new physics. He emphasised that physical knowledge comes to us from experimental measurement, and all measuring apparatus is classical in its behaviour. Laboratories are places where definite events happen—the pointer moves to a specific point on the scale and that is that. For Bohr, therefore, quantum theory was about what happens in a world containing these pieces of classical measuring apparatus. Its concern was with what could be said about experiments with electrons, not with what electrons actually were in themselves. He once wrote to a friend that

> There is no quantum world. There is only abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature is. Physics is concerned with what we can say about nature.[7]

One has to say that this positivist notion, asserting that science is simply concerned with talking about the results of experimental measurements, is not at all appealing to most of those who devote their lives to the hard work of scientific research. Rather, they believe that the payoff for all that demanding labour lies in the conviction that they are thereby learning more about the actual nature of the physical world. Without such a realist understanding, the work of science (and the discussions in this chapter) would lose much of their point.

There is also another problem with Bohr's point of view. He seemed to divide the world up into two parts: the accessible realm of classical measuring apparatus and the inaccessible realm of quantum entities, while insisting that they should always be considered linked together in a mutual engagement that he called a 'phenomenon'. This quasi-dualist picture cannot be right. Those reliable instruments in the laboratory are themselves composed of quantum constituents. There are not two distinct domains, but ultimately there is only one physical world.

An alternative way of thinking was to suppose that sys-

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[7] Quoted in M. Jammer, *The Philosophy of Quantum Theory*, Wiley, 1974, p. 204.

tems become more and more classical in their behaviour as they become 'large', so that a fuzzy world becomes clearer, and probabilities tend to move closer to certainties, as the relevant scale of events grows bigger. The existence of Planck's constant defines a measure in terms of which this idea of largeness can be expressed. It is worth exploring a mathematical way of formulating the notion, even if the going may be a little hard at times for the non-mathematical reader. The attempted trick lies in saying that quantum theory should turn into classical physics in the limit when $\hbar$ tends to zero. Of course, this is a formal device, since actually $\hbar$ is a constant with a specific magnitude in terms of physical units. It cannot literally be set equal to zero. Rather, using this mathematical strategy is a way of trying to express the expectation that classical behaviour will be manifested when Planck's constant is *very small* compared with the magnitudes of the quantities describing the actual system under consideration. It turns out that in some circumstances sense can be made of this idea, and when this is the case the emergence of classical-like behaviour is indeed obtained. Invoking this kind of transition from quantum to classical behaviour is called 'the correspondence principle' and Bohr, in fact, had made clever use of it in his early explorations of quantum phenomena. However, things are not always so straightforward. This is manifested mathematically by the fact that in the general case one cannot just take the formalism of quantum mechanics and put $\hbar=0$. The move fails because the limit of $\hbar$ tending to zero is what the mathematicians call singular. Expressions blow up and formulae become nonsensical. The general relationship between classical physics and quantum physics turns out to be delicate and subtle. This is the main point arising from the discussion that the non-mathematical reader needs to hold onto.

(Technical note: One can get some notion of the subtleties involved by considering Schroedinger's wavelike formulation of quantum physics. Adding two quantum waves, each of intensity 1 and travelling in opposite directions, does not give a single wave of intensity 2, but a wave whose intensity oscillates, varying between 0 and 4. In the limit as $\hbar$ tends to zero, this sum is found to fluctuate with ever-increasing frequency [this is a manifestation of the singularity of the limit]. Only when an average is taken over these rapid oscillations will the intuitively expected classical answer of 2 be obtained. [Think of two candles being twice as bright as one.] This averaging process is required to smooth out the singular behaviour.)

Bohr reminded us that measurement is some kind of engagement between quantum entities and classical-like apparatus. If we are not content to remain at a positivistic distance from what is involved, we shall soon encounter one of the great unsolved mysteries in the interpretation of quantum theory, the 'measurement problem'.[8] Once again our concern is with something for which it is worth a little effort to try to understand the nature of the issue.

A deep way of understanding why quantum theory is radically different from classical physics lies in the counterintuitive principle that the former allows one to add together, in a well-defined sense, states that classical physics and common sense would say are totally immiscible. For example (and the reader will just have to accept this strange fact), according to conventional quantum thinking, an entity such as an electron

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[8] Polkinghorne, *Quantum Theory*, pp. 44–56.

can be in a state which is a mixture of ‘being here’ and ‘being there’. This fundamental feature of quantum thinking is called ‘the superposition principle’.

When a measurement of position is made on this unpicturable state, there is a certain probability that the electron will be found in one place and a certain probability that it will be found in the other. Of course, when a definite measurement is actually made (essentially a kind of classical-like intervention by the measuring apparatus on the quantum entity), on any particular occasion one will get a definite answer, though not always the same answer on each occasion that the experiment is repeated. Sometimes the result will be ‘here’ and sometimes it will be ‘there’. This is the point at which probabilities come in. The relative frequencies of these results is something that the theory enables us to calculate with impressive accuracy, but it does not explain how it comes about that a particular answer is obtained on a particular occasion. This latter issue remains unresolved even after almost eighty years of successful exploitation of quantum theory itself. There is no universally accepted way of explaining how the fitful quantum world and the reliable classical world are joined to each other by the bridge of measurement. Here is a level transition within physics that so far remains beyond our understanding. We know how to do the sums, but we do not fully understand how it all works.

Many answers have been proposed to the measurement problem. In brief summary they include: (i) inducing a definite result is an effect of the irreversible behaviour of the large and complex systems that make the measurement (this is often called the (neo-)Copenhagen interpretation); (ii) some speculative form of (so far undiscovered) new physics brings it about; (iii) the intervention of human consciousness induces a determinate result; (iv) everything that might happen actually happens, but with different results appearing in the differing worlds of a proliferating multiverse; (v) it all depends upon the values of hidden variables of a Bohmian type; (vi) quantum physics refers to statistical ensembles and not to individual occurrences, so it just happens and that's that. Even so brief a catalogue makes it plain how diverse are the options that have been canvassed. It is not necessary to go into their details here, but we should note that none of them is wholly satisfactory in its current formulation. In consequence a very important joint in the causal nexus of the physical world remains problematic and controversial. Given the importance of measurement in science, it is embarrassing for a quantum physicist to have to admit this gap in our understanding.

As a result, no smooth and well-understood transition between quantum uncertainty and classical reliability is known to us. In particular, just appealing to a simple division between 'small' and 'large', however intuitively attractive that might at first sight seem to be, does not work. Not only are there many veiled consequences of quantum physics that are fundamental to the existence of a macroscopic world of the kind that is familiar to us (the stability of atoms and molecules would be a simple example), but there are further issues, soon to be considered, that indicate the subtle character of the mutual interpenetration of quantum theory and classical physics. The border between them is fractal-like rather than linear. They intermingle in complex ways. This lack of a fully integrated account of the two physical regimes means that the notion of a 'quantum event' is a much more problematic concept than many of those who appeal to it are prone to recognise.

Another failure of successful integration relates to the two greatest physical discoveries of the twentieth century, quantum theory and general relativity (the modern theory of gravity and spacetime structure). For more than eighty years they have remained imperfectly reconciled with each other, though there are contemporary hopes that the speculations of the string theorists might prove to be an important step in the direction of unification.[9] Presumably when a full theory of quantum gravity is attained, it will radically modify our ideas of the nature of space and time on the smallest conceivable scales (estimated to be about 10^{-33}cm and 10^{-43} sec respectively), since they will become subject to quantum fuzziness and the physical world may be expected to dissolve into some sort of spacetime 'foam' at its lowest level.

Within classical physics itself, there are also subtleties to be considered. The intricate nature of its causal properties is well illustrated by the discovery of chaos theory.[10] Towards the end of the nineteenth century the great French mathematician Henri Poincaré had come to realise that Newtonian theory was not as unproblematically predictable as his distinguished predecessor Pierre Simon Laplace had thought it natural to suppose. The latter had made his celebrated assertion that a 'calculating demon' of unlimited computational power, furnished with the details of the states of motion of all the particles in the universe as they are at the present moment, could predict the whole of the future and retrodict the whole of the past. However, Poincaré realised that there are many classical systems with the property that, though their equations

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[9] See B. Greene, *The Elegant Universe*, Jonathan Cape, 1999.

[10] See J. Gleick, *Chaos*, Heinemann, 1988.

appear mathematically deterministic, the solutions are exquisitely sensitive to the most minute detail of the initial conditions imposed upon them. The slightest variation in these conditions totally changes the expected future behaviour. (A toy model of such sensitivity would be a bead at the top of a smooth wire, bent in the shape of an inverted U. The slightest nudge will cause it to fall, but which side depends upon the fine detail of the disturbance. In more complex cases, bifurcations of possibility of this kind can accumulate without limit.)

The dead hand of mechanism was thereby released from macroscopic process, for the classical world was no longer perceived, even in principle, to be tame and reliably predictable. Putting it more picturesquely, there are at least as many disorderly clouds in the world as there are orderly clocks. Chaotic systems are inseparably linked to their environment, since the slightest external disturbance will radically affect their behaviour.

Systems with this property of extreme sensitivity do not need to be very complicated. An example that Poincaré studied was the problem of three bodies in mutual Newtonian gravitational attraction. There is no general solution of the kind the mathematicians call 'analytic' (smooth, well-behaved), because so many of the possible motions are chaotically sensitive and consequently unstably complicated.

These results of great sensitivity were rediscovered in the era of computerised calculations when Ed Lorenz came to realise that the equations that he was studying as a highly simplified model of a weather system did not produce similar solutions under very small changes of the input data. Instead, tiny initial variations induced completely different subsequent behaviour. The modern theory of chaos stems from this discovery. A number of the properties of chaotic dynamics are of great interest. We shall begin by considering the further subtle complications that chaos theory introduces into thinking about the relationship between classical physics and quantum theory.

The behaviour of a typical chaotic system soon comes to depend upon details of its initial configuration that require a degree of precise specification forbidden by Heisenberg's uncertainty principle. At first sight this fact might seem to offer the prospect of fusing quantum and classical characteristics, a process by which the consequences of the widely supposed indeterminacy of quantum phenomena might be amplified through chaotic dependence upon small detail to produce a widespread causal openness also in macroscopic phenomena. However, this idea is much more problematic than such a sketchy account indicates. The difficulty is that quantum theory and chaos theory do not fit neatly together. The reason for this is somewhat technical, but it is worth pursuing. It centres on the incompatibility of theories that have an intrinsic scale (like quantum theory) and those which do not (like chaos theory).

One way of indicating the mismatch is to note that quantum mechanics characteristically describes time dependence in terms of a discrete set of different frequencies (in this respect the spectra of atoms are similar to the fundamental and harmonics of an organ pipe), while chaotic dynamics has no characteristic frequencies, its time dependence corresponding to what is called mathematically a continuous spectral representation. As a result, quantum systems display periodic properties over long time intervals, a property that chaotic systems precisely do not possess. They are intrinsically aperiodic.

Another (and perhaps for the general reader, an even more mysterious) way of making the comparison is in terms of the differing properties of the geometrical structures that the theories generate in what the physicists call phase space. (One can think of this simply as a useful mathematical device for representing sets of possible motions.) We have already noted the presence in quantum theory of a scale set by Planck's constant. Effectively this means that quantum phase space is coarse-grained into a set of fuzzy regions of a size given by $\hbar$. In contrast, the phase space geometry associated with chaotic systems is fractal in its character, that is to say, it appears essentially the same on whatever scale it is sampled. (The paradigm example of fractal geometry is the celebrated Mandelbrot set. Take a small part of any representation of it, blow up the size of that part, and it will be found to be similar to the whole from which it was taken. The Mandelbrot set is, so to speak, 'the same all the way down' into its infinitesimal depths. It has no natural scale.) The mismatch between behaviour with a scale and behaviour that is scale-free has frustrated the development of a consistent unification of quantum and chaotic thinking in order to produce a theory of quantum chaology. In fact, one expects that the scaling imposed by quantum physics will have the effect of suppressing chaotic behaviour when the latter becomes sensitive to effects at the quantum level. Yet there is more still to be said about the problem, for further investigation of particular cases shows that the plot can thicken even more.

The highly complex character of physical causality in a realistic situation is illustrated by the tale of Hyperion, one of the moons of Saturn.[11] This irregularly shaped lump of rock, about the size of New York City, is observed to be tumbling chaotically as it encircles its planet. A simple estimate of the effectiveness of quantum physics in suppressing chaos, even when applied to a large object like Hyperion, leads to the conclusion that chaotic motion should not last for more than a finite period, in this case about thirty-seven years. While Hyperion has not been under observation for quite so long a time, no one expects that it is shortly about to return to orderly behaviour. It turns out that what will prevent this happening is a further influence, environmental in its character, which must also be taken into account. The effect is called decoherence, and in its turn it suppresses typical quantum effects. Decoherence arises from the fact that Hyperion is bathed in a sea of low-frequency radiation, partly coming from the Sun and partly from the universal cosmic background radiation that fills the universe. Interaction with this radiation represents a kind of repetitive 'measurement' process, continually erasing quantum fuzziness and restoring a classical-like situation, thereby preventing the quantum suppression of chaos from tightening its grip. It is rather like someone trying to get to sleep who continually asks himself 'Am I asleep yet?', thereby keeping himself awake. The decoherent suppression of quantum suppression will keep Hyperion tumbling for a very long time to come.

Until recently almost all thinking in mathematical physics

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[11] M. Berry in R. J. Russell, P. Clayton, K. Wegter-McNelly and J. C. Polkinghorne (eds), *Quantum Mechanics*, Vatican Observatory/CTNS, 2001, pp. 45–8.

made use of Newton's great discovery of the calculus, a technique perfectly adapted to the discussion of smoothly varying change. The fractal character of chaos is something altogether more jagged. States of motion that at present are infinitesimally close to each other will subsequently separate exponentially far apart. The onset of chaos is often signalled by a cascade of bifurcating possibilities as more and more options open up for future behaviour. In these endlessly diversifying kinds of circumstance, generalisations are called for that go beyond the 'nice' smooth properties that mathematicians associate with what they call 'integrable functions'. It becomes necessary mathematically to consider possibilities associated with jagged 'non-integrable' functions. From a physical point of view these complications arise from the existence of instabilities induced by what are called Poincaré resonances, endlessly active couplings between different possibilities of motion which frustrate the attainment of a clear, separable description. The resulting interlocking complexity dissolves the possibility of an itemised description of the system in terms of distinct trajectories and enforces the need for a purely statistical account of the character of nonintegrable systems. Ilya Prigogine has particularly emphasised this point of view. Speaking of the difference between individualised description (whether in terms of classical trajectories or quantum wave functions) and description in terms of a statistical ensemble, he says, 'Remarkably, at all levels, instability and nonintegrability break the equivalence of both descriptions'.[12] Prigogine believes that the forced move to an ensemble account is the reason for the existence of irreversible processes,

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[12] I. Prigogine, *The End of Certainty*, The Free Press, 1996, pp. 107–8.

characterised by an increase in entropy (the measure of the disorder in a system).

It has certainly been a long-standing puzzle in physics how fully to understand irreversibility, the emergence in the behaviour of complex systems of a definite direction for the arrow of time, distinguishing the past from the future, despite the fact that these systems arise from the combination of constituents whose fundamental interactions are symmetrical in character between past and future. We know that a film in which a broken glass reassembles itself is a film being run backwards (the true arrow of time of our macroscopic experience always points from order to disorder), but a film of two electrons interacting (were Heisenberg to allow one to record it) would make equal physical sense run in either direction. The reason that the time-reversed event regenerating the broken glass is not feasible is not because it is absolutely forbidden, but because it would require exquisitely precise correlations of the detailed motions and interactions of the returning fragments to a degree that it is just not possible to achieve. Disorder (broken glass) wins out over order (a perfect goblet) because there are overwhelmingly more ways of being disorderly than of being orderly. The increase of entropy in isolated systems, decreed by the second law of thermodynamics, is a manifestation of this preponderant tendency to anarchy. (An everyday analogy is the way that papers pile up higgledy-piggledy on your desk if you do not intervene to tidy it up occasionally.) Many believe that there are connections here with the quantum problem of measurement. Certainly the latter is irreversible, for it defines an arrow of time. Before one was ignorant; afterwards one knows the result. If it is indeed the irreversibility of macroscopic systems that elicits a specific result from making a measurement on a microscopic quantum entity, as the neo-Copenhagen interpretation of quantum theory suggests, this would then provide a striking example of the genuine flow of causal influence from the large to the small (what is often called 'top-down causality').

Yet it would be wrong to interpret the role of disorder as implying that physics describes a domain of the Miltonian 'reign of Chaos and Old Night'. In actual fact, the interlacing of order and disorder is precisely what seems to be needed for the creative emergence of novelty. New things happen in regimes that we have learned to identify as being 'at the edge of chaos'. Too far on the orderly side of that frontier and things are too rigid for there to be more than a shuffling rearrangement of already existing entities. Too far on the disorderly side, and things are too haphazard for any novelties to persist. A simple example of this principle is afforded by biological evolution. Without a degree of genetic mutation, life would be frozen into the existing range of forms. Too high a mutation rate, and there would be no quasi-stable species on which natural selection could operate.

'Chaos theory' has turned out to be an unfortunate misnomer. Order and disorder are found to interlace within its scenarios. All is not radical randomness. In dissipative chaotic systems (those in which friction operates), behaviour soon converges onto an intricate but limited portfolio of possible forms, called a 'strange attractor'. ('Attractor' indicates that motions converge upon it; 'strange' refers to the fractal character of its structure in phase space.) In those cases where chaos is generated through a cascade of bifurcating possibilities, there is a remarkable universal pattern in the way this happens, characterised by a new mathematical constant of fundamental significance, discovered by Michael Feigenbaum.[13]

A particularly interesting class of systems at the edge of chaos are those dissipative physical systems that are held far from thermal equilibrium by the continuous exchange of energy and entropy with their environment. All living entities have this character. Complete thermal equilibrium is a dull state of maximum entropy in which there is nothing really interesting left to happen. In contrast, systems far from equilibrium are ones in which small fluctuations can trigger the spontaneous generation of astonishing patterns of large-scale dynamical behaviour.[14] (Because these systems are not isolated but they are coupled to their environment, the second law of thermodynamics does not forbid this generation of orderly pattern, since a compensating degree of disorder is exported into the surroundings.) A simple example of this behaviour is provided by Bénard convection. When a fluid contained between two horizontal plates is heated from below, an appropriate temperature difference between the bottom and top can induce a striking phenomenon in which the convective motion of the fluid is contained within a pattern of hexagonal convection cells. This behaviour corresponds to the correlated motion of trillions upon trillions of molecules.

The unexpected degree of novel behaviour displayed by dissipative systems certainly illustrates the point that that more can be different. Similar properties have been discovered by complexity theorists, whose work so far has mostly centred on the natural history–like observation of the properties of

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[13] See Gleick, *Chaos*, pp. 171–81.

[14] I. Prigogine and I. Stengers, *Order out of Chaos*, Heinemann, 1984.

moderately complicated computer-generated models. Stuart Kauffman has discussed a particularly interesting example.[15] Its logical form is that of a Boolean net of connectivity 2, but it is easier to visualise the system in terms of a hardware equivalent. Consider a large array of electric light bulbs, each of which has two possible states, ‘on’ and ‘off’. The system develops in steps and there are simple rules determining its state at the next step from its state now. Each bulb is correlated with two other bulbs somewhere else in the array and the rules specify how the bulb’s next state is derived from the present state of the two bulbs that are its correlates. The array is started off in a configuration of random illumination, some bulbs on and some bulbs off. It is then left to develop according to the rules. One might have expected that generally nothing very interesting would happen and that the array would just twinkle away haphazardly for as long as it was let to do so. In fact, this is not at all the case. If there are 10,000 bulbs in the array, the number of possible states of illumination possible in principle is $2^{10,000}$, or about $10^{3,000}$, an absolutely huge number. Yet, the system soon settles down to cycling through only about one hundred states! (In more general terms, if there are N bulbs in the array, the number of patterns of illumination finally realised in this way is about $N^{1/2}$.) This phenomenon represents the spontaneous generation of an altogether astonishing degree of order. Once again, more seems to be different in a highly non-trivial manner. Similar spontaneous generation of complex order is also found to occur in systems of cellular automata.[16]

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[15] S. Kauffman, *At Home in the Universe*, Oxford University Press, 1995, ch. 4.

[16] S. Wolfram, *A New Kind of Science*, Wolfram Media, 2002.

At present no general theory is known that covers the behaviour of complex systems, either physical or logical, though the remarkable results sporadically discovered through the investigation of particular cases strongly encourage the expectation that there is a deep theory underlying these examples and awaiting discovery. Progress towards a general understanding may be expected to require a revolution in scientific thinking in the twenty-first century at least as great as that wrought by the discovery of quantum theory in the twentieth century. Two features may be expected to characterise this conceptual development when it arrives.

One is the recognition of the inadequacy of a merely reductionist account, so that the addition of a complementary holistic discourse will be needed, treating entities in the integrity of their wholeness. More is indeed different. None of the remarkable pattern-generating properties of the systems discussed could have been guessed from thinking about their individual components.

It is interesting to note that even so superficially reductionist a subject as the quantum physics of elementary particles provides support for the need for an holistic dimension in our approach to physical reality. Albert Einstein, Nathan Rosen and Boris Podolsky discovered in 1935 that quantum theory implied a counterintuitive togetherness-in-separation (non-locality) for two quantum entities that had interacted with each other. If they separate from each other, even to a great distance apart, they nevertheless remain mutually entangled with each other, so that acting on the one ‘here’ (say, measuring one of its properties) has an immediate causal effect on the other, no matter how far away it may be. (This is the celebrated 'EPR effect'.)[17] What happens to the distant entity depends specifically upon what happens to the near one, so that the effect is genuinely causal and not merely epistemological, as if it just involved learning about something that was already the case. Of course, there is nothing surprising about the latter. If there are two balls in an urn, one white and the other black, and we each take out one in our closed fists, then if you go a mile down the road before I open my hand, if I see a white ball I know immediately that you have a black one. This was always so and all that has happened is that I have now learned that it is the case. In contrast, the EPR effect is rather like saying that if I found a red ball, then your ball would have had to be to be green, but if I had found a blue ball, yours would have had to be orange. Einstein himself felt that the EPR phenomenon was so 'spooky' that its prediction showed there must be some shortcoming in quantum theory, but later experiments have confirmed that non-locality is indeed a property of nature. Even subatomic particles, it seems, cannot properly be treated atomistically! The apparent localisability of the objects of our everyday experience is not as unproblematic as it might have seemed to be, a thought reinforced when one remembers the sensitivity of chaotic systems to the smallest disturbance arising from their environment.

The other conceptual development will surely be the placing of 'information' alongside 'energy' to form a joint basis for fundamental thinking. By information is meant something like the appropriate specification of dynamical patterns of ordered behaviour. While the concept of information is intuitively appealing, and the idea of it has been cited

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[17] Polkinghorne, *Quantum Theory*, ch. 5.

recently in many contexts of reflection on the character of the natural world, its specification in more precise terms is a matter of continuing discussion and difficulty. Two possible sources of insight, in particular, have been canvassed. One has been Claude Shannon's theory of communication; the other is computer science.[18] In the former case an important aim is to prevent messages becoming garbled because of interference from background noise. In order to combat this degradation, a degree of redundancy is desirable in the form of the message. (Most mail addresses include both the street name and the postcode. If the postman cannot decipher the one, he may fare better with the other and so the letter will get through.) The appeal to computer science has been aimed particularly at finding some acceptable measure of intrinsic complexity. An informational statement written in binary code (0s and 1s) might be very long but the programme specifying it might be very much shorter, for example 'print 01 a million times'. In this case the specification is said to be algorithmically compressible—it is much shorter than the message itself—and the system it refers to is correspondingly simple. In the converse case, algorithmic incompressibility becomes a signal of complexity and potential richness of informational specificity. However, there are no general meta-algorithms for determining the shortest programme that will do the trick.[19] Difficulties of this kind beset approaches to information that rely on computer science. In addition, like the ideas derived from communication theory, they are strictly syntactical in

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[18] Gleick, *Chaos*, pp. 255–9; H. C. von Baeyer, *Information*, Weidenfeld and Nicholson, 2003.

[19] See D. Ruelle, *Chance and Chaos*, Princeton University Press, 1991, chs 21–23.

character and so they bracket out any consideration of the semantic issues of meaningfulness and significance.

We have seen that there is much evidence to support the thesis that 'More is different', since strikingly novel properties emerge in complex systems. There remains, however, the central question of the kind of emergence that is being observed. Is it only weak or can we suppose there are cases where the strong criterion of causal novelty is satisfied? In terms of a hierarchy of levels of complexity, notions of 'top-down causation', by means of which the whole influences the behaviour of the parts,[20] or of the 'supervenience' of a higher level upon a lower, so that both kinds of discourse are simultaneously admitted,[21] are certainly attractive, but they are not unproblematic and in the absence of an actual causal analysis they would seem to be aspirations rather than proposals. We shall not really be able to speak of strong emergence unless it can be argued that the lower level does not soak up all the available causal room for manoeuvre.

We have seen that the nature of the causal nexus of the world is ultimately a matter for metaphysics rather than physics. If the latter reports an epistemic deficit in its account due to the existence of intrinsic unpredictabilities (as both quantum theory and chaos theory actually indicate), then there is an opportunity for the metaphysician to propose that these represent not merely ignorances arising from unfortunate epistemological limitation, but they correspond to actual ontological openness, allowing the operation of further causal principles, active in bringing about the future, beyond those

[20] Peacocke, *Theology*, pp. 53–5, 157–60.

[21] N. Murphy in R. J. Russell, N. Murphy, T. C. Myerling and M. A. Arbib (eds), *Neuroscience and the Person*, Vatican Observatory, 1999, pp. 147–64.

that a reductionist physical theory is able to describe. Those who embrace a realist philosophy of science, aligning epistemology and ontology as closely as possible to each other from the conviction that what we know or cannot know is a reliable guide to what is the case, would seem almost to be obligated to take this point of view.

The 'laws' of physics discovered at low levels of complexity would then simply be 'downward-emergent' approximations to the character of a more subtle and supple causal story in which the whole truly did influence the behaviour of the parts. (I have called this latter stance 'contextualism'.)[22] The approximation involved in this downward emergence would correspond to the idealisation that the system considered could effectively be treated as being isolated from the influence of its total environment. Such circumstances are sometimes attainable—the feasibility of experimental science depends upon this being the case, for otherwise it would not be possible to investigate anything without having to take everything into account—but the exquisite sensitivity of chaotic systems to any disturbance arising from their surroundings, together with the EPR effect, shows that isolatability is far from being a universal property. We therefore have no compelling grounds for regarding current theories as being more than a form of approximation to actual physical reality as it is encountered in the limit of effective isolatability. While the laws of classical physics taken at face value do indeed exhibit the phenomenon of 'deterministic chaos' (apparently haphazard behaviour arising from solutions of mathematically pre-

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[22] J. C. Polkinghorne, *Science and Christian Belief/The Faith of a Physicist*, SPCK/Fortress, 1994/1996, p. 29.

cise and deterministic equations), it is a matter for *metaphysical* decision, similar to the decision between the rival interpretations of quantum physics offered by Bohr and Bohm, to conclude what this tells us about the causal nexus of the world. I personally have espoused a realist interpretation that treats chaotic unpredictability as a sign of ontological openness.[23] The expectation of a generalised correspondence principle linking the true theory to its localised approximation encourages the thought that appeal to significant general features of chaos (sensitivity to detailed circumstance; structures similar to strange attractors) will not prove misleading, even though the two accounts must differ in certain respects, as the discussion of the problems of quantum chaology has already made clear.

Making use of science's account of future behaviour in this open metaphysical way by no means demands us to abandon the principle of sufficient reason, requiring a full explanation of the origin of what actually occurs. It is simply to conceive that the portfolio of causes that bring about the future is not limited solely to the description offered by a methodologically reductionist physics and framed only in terms of the exchange of energy between constituents. Instead, the concept of causal influence can be broadened at least to include holistic effects of an informational, pattern-forming kind. One might call this top-down form of causality 'active information'. Such a move could then represent a small step in the direction of the more ambitious metaphysical programme represented by *dual-aspect monism*. This philosophical scheme aims to treat

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[23] J. C. Polkinghorne, *Belief in God in an Age of Science*, Yale University Press, 1998, ch. 3; *Faith, Science and Understanding*, Yale University Press, 2000, pp. 99–101.

the mental and the material as complementary poles of the one world-stuff, perceived in different modes of encounter.[24] Regarded from this wider metaphysical standpoint, the duality of energy and information that science is beginning to embrace might prove to be part of a movement towards the attainment of an understanding that takes with equal seriousness our basic human experiences of physical embodiment and of personal agency. The task of carrying this project further would, of course, require very much greater enrichment of the concept of information, moving it on from purely syntactical considerations to enable it to accommodate also semantic dimensions of critical significance in relation to an account of intentional action. Not only would this move provide an improved basis for the understanding of human agency, so that the metascientific discourse would begin to describe a world of which we could fittingly conceive ourselves as being inhabitants, but it could also refer to a physical world within whose open grain it would be fully conceivable that the God who is that world's Creator is providentially at work through the input of active information into its unfolding history, in a manner that operates non-interventionally within the grain of nature, rather than interventionally against it. This is an idea that I have explored elsewhere.[25]

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24. T. Nagel, *The View from Nowhere*, Oxford University Press, 1986, pp. 28–32.

25. Polkinghorne, *Belief in God*, ch. 3. For a defence of the idea that God may act causally within the openness of the created order, rather than in some ineffable way unique to deity, see J. C. Polkinghorne (ed.), *The Work of Love*, SPCK/Eerdmans, 2001, pp. 104–5. For surveys of current ideas about divine action, see P. Clayton, *God and Contemporary Science*, Edinburgh University Press, 1997, chs 5–8; N. Saunders, *Divine Action and Modern Science*, Cambridge University Press, 2002; W. Wildman, 'The Divine Action Project, 1988–2003', *Theology and Science*, 2, pp. 31–75 (2004).

At present, these ideas necessarily remain largely hopes for future understanding. What one can say, both in relation to human agency and in relation to divine providential action, is that the proper acknowledgement of our fragmented knowledge of the causal structure of physical reality is at least sufficient to 'defeat the defeaters', to challenge and put in question those who are trying to assert the necessity of a merely physical reductionist view. It is clear that science has not demonstrated the causal closure of the natural world. Nothing it can tell us requires us to deny our directly experienced human capacity for intentional action, nor can science forbid religious believers to hold to their belief in God's providential interaction with the history of the world.