INFORMATION AND THE NATURE OF REALITY

From Physics to Metaphysics

EDITED BY

Paul Davies and Niels Henrik Gregersen

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From Physics to Metaphysics

Many scientists regard mass and energy as the primary currency of nature. In recent years, however, the concept of information has gained importance.

In this book, eminent scientists, philosophers, and theologians chart various aspects of information, from quantum information to biological and digital information, in order to understand how nature works. Beginning with a historical treatment of the topic, the book also examines physical and biological approaches to information, and the philosophical, theological, and ethical implications.

Information and the Nature of Reality

From Physics to Metaphysics

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To the memory of Arthur R. Peacocke (1924–2006)

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PAUL DAVIES (PhD London, 1970) has held university positions at Cambridge, London, Newcastle, Adelaide, and Sydney before joining Arizona State University as Professor and Director of Beyond: Center for Fundamental Concepts in Science. He has helped develop quantum field theory, and alongside his scientific work in cosmology and atomic astrophysics he has maintained interests in the origin of time asymmetry and astrobiology. He has written more than 25 books, both popular and specialist works, including *About Time* (1995), *The Fifth Miracle* (1998), *How to Build a Time Machine* (2002), *The Goldilocks Enigma* (2007) and *The Eerie Silence* (2010). He has received many awards, including the 2001 Kelvin Medal, the 2002 Faraday prize, and in 1995 the Templeton Prize.

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ARTHUR R. PEACOCKE (1924–2006) was a biochemist and theologian from Oxford University. Having taught at Birmingham he returned to Oxford in 1959 as Professor of Physical Biochemistry. In this capacity he published more than 125 papers and three books. Later he resumed his theological interests, became ordained in 1971, and went to serve as Dean of Clare College, Cambridge University. In 1985 he became the founding director of the Ian Ramsey Centre, at Oxford. In 1992–1993 he gave the Gifford Lectures, published as *Theology for a Scientific Age* (1993). In a series of books, beginning with *Science and the Christian Experiment* (1971) and ending with *All That Is: A Naturalistic Faith for the Twenty-First Century* (2007), he laid the groundwork for a generation of younger scholars in the field of science and religion. In 2001 he was awarded the Templeton prize.

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JOHN MAYNARD SMITH (1920–2004) was a geneticist and theoretical evolutionary biologist. In the late 1950s and early 1960s he did pioneering work on the genetics of aging in fruit flies, and wrote *The Theory of Evolution* (1958). As the Founding Dean of the School of Biological Sciences at the University of Sussex (1965–1985), his interests turned into theoretical problems of evolutionary biology, especially concerning the relation between mathematics and life. He formalized the Evolutionary Stable Strategy (EES), today a standard tool in game theory. His classic works in theoretical biology include *The Evolution of Sex* (1978), *Evolution and the Theory of Games* (1982), and *The Major Transitions in Evolution* (with E. Szatmáry, 1997).

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KEITH WARD is Emeritus Regius Professor of Divinity at Oxford University, Professorial research fellow at Heathrop College, London, and Fellow of the British Academy. Laid out in more than 25 books, his work covers wide areas, from systematic and philosophical theology to comparative theology and science and religion. In 2008 he finished a five-volume series of comparative theology, comparing the great religious traditions on concepts of revelation, creation, human nature, and community. Also in the field of science and religion he has produced a number of influential books, including more recently *Pascal's Fire: Scientific Faith and Religious Understanding* (2006) and *The Big Questions in Science and Religion* (2008).

MICHAEL WELKER held faculty positions at the universities in Tübingen and Münster before he was offered the Chair of Systematic Theology at Heidelberg in 1991. He has been Director of the University's Internationales Wissenschaftsforum and is currently the Director of the Research Center for International and Interdisciplinary Theology. His method is to work through Biblical traditions as well as through contemporary philosophical, sociological, and scientific theories to address questions of contemporary culture and religion. His influential works in theology include *Creation and Reality* (1999), *What Happens in Holy Communion?* (2000), and *God the Spirit* (2004). Contributions to science and religion include *The End of the World and the Ends of God* (2000) and *Faith in the Living God* (with John Polkinghorne, 2001).

Acknowledgments

This book grew out of a symposium held in the Consistorial Hall of Copenhagen University on 17–19 August 2006 under the aegis of the John Templeton Foundation and the Copenhagen University Research Priority Area on Religion in the 21st Century. The aim of the conference was to explore fundamental concepts of matter and information in current physics, biology, philosophy and theology with respect to the question of ultimate reality.

We, the editors and co-chairs, arranged the symposium 'God, Matter and Information. What is Ultimate?' in close collaboration with Dr Mary Ann Meyers, the Director of the Humble Approach Initiative under the John Templeton Foundation. The Humble Approach supports cutting-edge interdisciplinary research, insofar as it remains sensitive to disciplinary nuances, while looking for theoretical linkages and connections. Such studies are especially needed in areas of research that are central to the sciences, pertinent for a contemporary metaphysics, and yet are difficult to conceptualize and present in overview.

We are grateful to Mary Ann Meyers for her ongoing enthusiasm and expertise, and to the John Templeton Foundation for sponsoring the symposium so generously. We also want to thank the Editorial Director of Cambridge University Press, Dr Simon Capelin, for his assistance and encouragement in the publication of this book, and the anonymous peer reviewers who supported it. Lindsay Barnes and Laura Clark of the Press have set the editorial standards for this volume and worked in close collaboration with graduate student Trine-Amalie Fog Christiansen at Copenhagen University, who worked as a research assistant on this book and time and again showed her analytical skills. We owe thanks to her, and to Mikkel Christoffersen for assisting in the last phase of the production and for preparing the index.

With two exceptions, all papers grew out of the Copenhagen symposium. We asked Professor Philip Clayton to write a brief philosophical history of the concept of matter, with special emphasis on modernity, and we thank him for doing this so swiftly and well. We also wanted to include the programmatic article of the late evolutionary biologist John Maynard Smith, 'The Concept of Information in Biology' (*Philosophy of Science* 67(2), June 2000); we acknowledge the journal for giving us the permission to reprint this article as Chapter 7 of this volume.

This volume is dedicated to the memory of Arthur Peacocke who, sadly, died on 21 October 2006. Arthur Peacocke was part of the group, but because of his illness he could not attend the conference, so his paper was discussed in his absence. Chapter 12 in this volume is one of the last works from his hand. Peacocke's research in biochemistry and in the intersection of theology and science is highly regarded, and his intellectual testimony can found in his posthumous *All That Is: A Naturalistic Faith for the 21st Century* (Fortress Press, 2007). But for many of us, Arthur was not just a great scholar, but a mentor, a fellow-inquirer, and a friend who continued to listen, explore, and ask for more. We are indeed indebted to Arthur for his personal combination of rigour and generosity.

1 Introduction: does information matter?

Paul Davies and Niels Henrik Gregersen

It is no longer a secret that inherited notions of matter and the material world have not been able to sustain the revolutionary developments of twentieth-century physics and biology. For centuries Isaac Newton's idea of matter as consisting of 'solid, massy, hard, impenetrable, and movable particles' reigned in combination with a strong view of laws of nature that were supposed to prescribe exactly, on the basis of the present physical situation, what was going to happen in the future. This complex of scientific materialism and mechanism was easily amalgamated with common-sense assumptions of solid matter as the bedrock of all reality. In the world view of classical materialism (having its heyday between 1650 and 1900), it was claimed that all physical systems are nothing but collections of inert particles slavishly complying with deterministic laws. Complex systems such as living organisms, societies, and human persons, could, according to this reductionist world view, ultimately be explained in terms of material components and their chemical interactions.

However, the emergence of thermodynamics around 1850 already began to cast doubt on the universal scope of determinism. Without initially questioning the inherited concepts of corpuscular matter and mechanism, it turned out that the physics of fluids and gases in thermodynamically open systems can be tackled, from a practical point of view, only by using statistical methods; the aim of tracking individual molecules had to be abandoned. In what has been aptly been called *The Probabilistic Revolution* (Krüger, Daston, and Heidelberger, 1990), determinism became a matter of metaphysical

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belief rather than a scientifically substantiated position. By the 1870s a great physicist such as James Clerk Maxwell was already questioning the assumption of determinism by pointing to highly unstable systems in which infinitesimal variations in initial conditions lead to large and irreversible effects (later to become a central feature of chaos theory). It was not until the twentieth century, however, that the importance of non-equilibrium dissipative structures in thermodynamics led scientists such as Ilya Prigogine (1996) to formulate a more general attack on the assumptions of reversibility and scientific determinism.

What happened, then, to the notion of matter and the material? In a first phase the term 'matter' gradually lost its use in science to be replaced by more robust and measurable concepts of mass (inertial, gravitational, etc). The story of the transformations of the idea of matter into something highly elusive yet still fundamental is told in detail by Ernan McMullin and Philip Clayton in Chapters 2 and 3 of this volume. Here it suffices to point to three new developments of twentieth-century physics in particular that forced the downfall of the inherited Matter Myth, and led to new explorations of the seminal role of information in physical reality.

The first blow came from Einstein's theories of special relativity (1905) and general relativity (1915). By stating the principle of an equivalence of mass and energy, the field character of matter came into focus, and philosophers of science began to discuss to what extent relativity theory implied a 'de-materialization' of the concept of matter. However, as McMullin points out, even though particles and their interactions began to be seen as only partial manifestations of underlying fields of mass-and-energy, relativity theory still gave room for some notion of spatio-temporal entities through the concept of 'rest mass'.

The second blow to classical materialism and mechanism came with quantum theory, which describes a fundamental level of reality, and therefore should be accorded primary status when discussing the current scientific and philosophical nature of matter.

In Chapters 4, 5, and 6 Paul Davies, Seth Lloyd, and Henry Pierce Stapp challenge some widely held assumptions about physical reality. Davies asks what happens if we do not assume that the mathematical relations of the so-called laws of nature are the most basic level of description, but rather if *information* is regarded as the foundation on which physical reality is constructed. Davies suggests that instead of taking mathematics to be primary, followed by physics and then information, the picture should be inverted in our explanatory scheme, so that we find the conceptual hierarchy: information → laws of physics → matter. Lloyd's view of the computational nature of the universe develops this understanding by treating quantum events as 'quantum bits', or qubits, whereby the universe 'registers itself'. Lloyd approaches this subject from the viewpoint of quantum information science, which sets as a major goal the construction of a quantum computer – a device that can process information at the quantum level, thereby achieving a spectacular increase in computational power. The secret of a quantum computer lies with the exploitation of genuine quantum phenomena that have no analogues in classical physics, such as superposition, interference, and entanglement. Quantum computation is an intensely practical programme of research, but Lloyd uses the concept of quantum information science as the basis for an entire world view, declaring that the universe as a whole is a gigantic quantum computer. In other words, nature processes quantum information whenever a physical system evolves.

Lloyd's proposal forms a natural extension of a long tradition of using the pinnacle of technology as a metaphor for the universe. In ancient Greece, surveying equipment and musical instruments were the technical wonders of the age, and the Greeks regarded the cosmos as a manifestation of geometric relationships and musical harmony. In the seventeenth century, clockwork was the most impressive technology, and Newton described a deterministic clockwork universe, with time as an infinitely precise parameter that gauged all cosmic change. In the nineteenth century the steam engine replaced clockwork as the technological icon of the age and, sure enough, Clausius, von Helmholtz, Boltzmann, and Maxwell described the universe as a gigantic entropy-generating heat engine, sliding inexorably to a cosmic heat death. Today, the quantum computer serves the corresponding role. Each metaphor has brought its own valuable insights; those deriving from the quantum computation model of the universe are only just being explored.

In the absence of a functional quantum computer, the most powerful information-processing system known is the human brain (that may change soon, as even classical computers are set to overtake the brain in terms of raw bit flips). The relationship between mind and brain is the oldest problem of philosophy, and is mirrored in the context of this volume by the information–matter dichotomy. Crucially, the brain does more than flip bits. Mental information includes the key quality of semantics; that is, human beings derive understanding of their world from sense data, and can communicate meaning to each other. The question here is what can, and what cannot, be explained merely by digital information, which is formulated in terms of bits without regard to meaning. When the foundation for information theory was laid down by Shannon, he purposely left out of the account any reference to what the information means, and dwelt solely on the transmission aspects. His theory cannot, on its own, explain the semantics and communication of higher-order entities. At most, one could say, as Deacon suggests in Chapter 8, that Shannon focused on the syntactic features of an information potential.

The foregoing properties of the mental realm are closely related to the issue of consciousness. How the brain generates conscious awareness remains a stubborn mystery, but there is a well-established school of thought that maintains it has something to do with quantum mechanics. Certainly the role of the observer in quantum mechanics is quite unlike that in classical mechanics. Moreover, if quantum mechanics really does provide the most fundamental description of nature, then at some level it must incorporate an account of consciousness and other key mental properties (for example, the emergence of semantics, the impression of free will). For many years, Henry Stapp has championed the case for understanding the mind and its observer status in a quantum context, and in Chapter 6 he sets out a well-argued case both for taking consciousness seriously (that is, not defining it away as an epiphenomenon) and for accommodating it within a quantum description of nature.

The third challenge to the inherited assumptions of matter and the material comes from evolutionary biology and the new information sciences, which have made revolutionary discoveries since the 1940s and 1950s. Placed at the interface of the physical and cultural sciences, biology plays a pivotal role in our understanding of the role of information in nature. In Chapter 7 John Maynard Smith argues that the biological sciences must be seen as informational in nature, since the sequence structure of DNA is causally related, in a systematic way, to the production of proteins. In the nineteenth century, living organisms were viewed as some sort of magic matter infused with a vital force. Today, the cell is treated as a supercomputer – an information-processing and -replicating system of extraordinary fidelity. The informational aspects of modern molecular biology are conspicuous in the way that gene sequencing and gene pathways now form the foundation for understanding not only evolutionary biology, but also cell biology and medicine. In Chapters 8 and 9 Terrence Deacon and Bernd-Olaf Küppers offer two distinct naturalistic views about how the crucial *semantic* levels of information might emerge via thermodynamical (Boltzmann) and evolutionary (Darwinian) processes. Both accounts argue that biological information is not only instructional but also has to do with 'valued' or 'significant' information, which puts the receiver in the centre of interest. Significant information, however, is always a subset of a wider set of informational states, which may be described as the underlying 'information potential'. With this background, Deacon presents a naturalistic theory of the emergence of contextual information; that is, the capacity for reference and meaning, which he describes in terms of the notion of 'absent realities'. This he accomplishes by combining the Shannon–Boltzmann view that information is always relative to a statistical information potential, with the Darwinian emphasis on what actually works for an organism in its pragmatic setting. In Chapter 10 Jesper Hoffmeyer then presents a biosemiotic proposal, which questions the overarching role of genetics, and rather opts for the importance of a cell-centred view. Finally, in Chapter 11, Holmes Rolston offers a natural history of the emergence of an informed concern for others. Evolution is a notoriously 'selfish' process, but eventually it generates systems that display altruism and exhibit concern for other beings. With the increase of sense perception and the top-down capacities of mammalian brains, an ethical dimension of nature arrives on the evolutionary scene. A cell-centred view is not necessarily a self-centred view.

It would be wrong to claim that the science-based chapters collectively amount to an accepted and coherent new view on the fundamental role of information in the material world. Many scientists continue to regard matter and energy as the primary currency of nature, and information to be a secondary, or derived concept. And it is true that we lack the informational equivalent of Newton's laws of mechanics. Indeed, we do not even possess a simple and unequivocal physical measure for information, as we have for mass and energy in terms of the units of *gram* and *joule*. Critics may therefore suspect that 'information' amounts to little more than a fashionable metaphor that we use as a shorthand for various purposes, as when we speak about information technologies, or about anything that is 'structured', or some way or another 'makes sense' to us.

The incomplete nature of information theory is exemplified by the several distinct meanings of the term 'information' used by the contributors in this volume. Quantum events as informational qubits (Lloyd), for example, have a very different character from Shannon-type digital information, or as mere patterns (Aristotelian information), and none of the foregoing can much illuminate the emergent concept of *meaningful* information (semantic information). In spite of the tentative nature of the subject, however, two reasons can be offered for giving information a central role in a scientifically informed ontology. The main point is that information makes a causal difference to our world – something that is immediately obvious when we think of human agency. But even at the quantum level, information matters. A wave function is an encapsulation of *all that is known* about a quantum system. When an observation is made, and that encapsulated knowledge changes, so does the wave function, and hence the subsequent quantum evolution of the system. Moreover, informational structures also play an undeniable causal role in material constellations, as we see in, for example, the physical phenomenon of resonance, or in biological systems such as DNA sequences. What is a gene, after all, but *a set of coded instructions* for a molecular system to carry out a task? No evolutionary theory can have explanatory function without attending to the instructional role of DNA sequences, and other topological structures. But neither can a bridge or skyscraper be constructed successfully without paying due attention to the phenomenon of resonance, and so it seems that just as *informational events* are quintessential at the lowest level of quantum reality, so are *informational structures* quintessential as driving forces for the historical unfolding of physical reality.

The philosophical perspectives of a material world based on an irreducible triad of mass, energy, and information are discussed in the contributions in the section on philosophy and theology. In Chapter 12 the late biologist and theologian Arthur Peacocke (to whom this book is dedicated) presents his integrative view about how an emergentist monism, informed by the sciences of complexity, must be sensitive to the uniformity of the material world as well as to the distinctive levels that come up at later stages of evolution. Peacocke's theological synthesis thus combines naturalism and emergentism with a panentheistic concept of God; that is, God permeates the world of nature from within, although God is more than the world of nature in its entirety. Peacocke's religious vision is thus developed within the horizon of what he calls EPN (emergentist/monist–panentheistic–naturalist). In Chapters 13 and 14 the philosophical theologians Keith Ward and John F. Haught explore novel ways for understanding God as the source of information for a self-developing world. Ward argues for what he calls a supreme informational principle of the universe, without which the combination of the lawfulness of the world and its inherent value would be inexplicable. Such informational code for construction of an actual universe logically precedes material configurations by containing the set of all mathematically possible states, plus a selective principle of evaluation that gives preference to the actual world that we inhabit. Ward suggests that this primary ontological reality may be identified with God, especially if the given laws of nature can be seen as providing space for qualities such as goodness and intrinsic value. Haught argues that information must walk the razor's edge between redundancy (too much order) and noise (too much contingency). It is this felicitous blend of order and novelty that transforms the universe from a mere physical system into a narrative of information processing. While reminding us that all 'God language' must be regarded as analogical, he argues that the concept of God as an informational principle at work in the entire cosmic process is far richer than the idea of a designer God at the edge of the universe. While emphasizing the logical space of all nature (Ward) and the evolutionary unfolding thereof (Haught), both draw on contemporary scientific accounts of nature that accord with, or even suggest, a divine reality with world-transforming capacities. A science-based naturalism may thus still allow a distinction between the world of nature (with a small 'w') and the World in extenso (with a capital 'W'). Finally, in Chapters 15 and 16, Niels Henrik Gregersen and Michael Welker argue that the new scientific perspectives of matter and information summarized in this volume give fresh impetus to a reinterpretation of important strands of the Biblical traditions. Gregersen shows how the New Testament concept of a 'divine Logos becoming flesh' (John 1:14) has structural similarities to the ancient Stoic notion of Logos as a fundamental organizing principle of the universe, and should not prematurely be interpreted in a Platonic vein. The Johannine vision of divine Logos being coextensive with the world of matter may be sustained and further elucidated in the context of present-day concepts of matter and information, where the co-presence of order and difference is also emphasized. A typology of four types of information is presented, reaching from quantum information to meaning information. In the final essay, Welker suggests that interdisciplinary discussions (between science, philosophy, and theology) should be able to move between more general metaphysical proposals and the more specific semantic universes, which often are more attentive to the particulars. One example is Paul's distinction between the perishable 'flesh' and the possibility of specific 'bodies' being filled with divine energy. Such distinctions may also be able to catch the social dimensions of material coexistence, which are left out of account in more generalized forms of metaphysics. According to Paul, the divine Spirit may saturate the spiritual bodies of human beings and bring them into communication, when transformed in God's new creation.

Our hope is that the selection of essays presented in this volume will open a new chapter in the dialogue between the sciences, philosophy, and theology.

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Part I **History**

2 From matter to materialism … and (almost) back

Ernan McMullin

The matter concept has had an extraordinarily complex history, dating back to the earliest days of the sort of reflective thought that came to be called 'philosophy'. History here, as elsewhere, offers a valuable means of understanding the present, so it is with history that I will be concerned – history necessarily compressed into simplified outline.

This story, like that of Caesar's Gaul, falls readily into three parts. First is the gradual emergence in early Greek thought of a factor indispensable to the discussion of the changing world and the progressive elaboration of that factor (or, more exactly, cluster of factors) as philosophic reflection deepened and divided. Second is the radical shift that occurred in the seventeenth century as the concept of matter took on new meanings, gave its name to the emerging philosophy of materialism and yielded place to a derivative concept, mass, in the fast-developing new science of mechanics. Third is the further transformation of the concept in the twentieth century in the light of the dramatic changes brought about by the three radically new theories in physics: relativity, quantum mechanics, and expanding-universe cosmology, with which that century will always be associated. Matter began to be dematerialized, as it were, as matter and energy were brought into some sort of equivalence, and the imagination-friendly particles of the earlier mechanics yielded way to the ghostly realities of quantum theory that are neither here nor there.

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2.1 PHASE ONE: ORIGINS

Aristotle was the first to adapt a term from ordinary usage in order to anchor the technical analysis of change that is at the heart of his physics (Johnson, 1973; McMullin, 1965). *Hylē* (rendered as *materia* in Latin) originally designated the timber used, for example, in the construction of a house, the materials of a making. But long before Aristotle, the very first Greek philosophers sought to specify the 'stuff' from which they believed all things to have originally come, a stuff that would have familiar sense-properties that would help to make cosmic origins intelligible. Some went on to intimate that this is also the stuff of which all things are now composed. They disagreed as to what that stuff might be – water, fire, atoms, seeds, ... – and they lacked any generic term for the stuff itself. But the notion that there should be something or other that underlay not only origins but perhaps all change was a key feature of the thinking of these first Ionian 'philosophers'.

Nor did Plato later have a specific term to play the role, for him quite central, that would later be assigned to matter (Eslick, 1965). The search that forever occupied him was for intelligibility, and this he found in the first instance in mathematics, where Reason can discern Forms that are beyond the reach of change, the enemy of intelligibility. The world of sense is a changing world, and by that very fact it is for Plato only imperfectly intelligible. Forms are instantiated there; but the Form of a triangle, say, is only imperfectly realized in the multiplicity of objects in the sense world that can pass as triangular. What makes this sort of multiplicity possible is the presence of a Receptacle, existent in its own right, somewhat akin to what we would call 'space'.

The Receptacle is what makes the sense-world possible. It instantiates an indefinitely great number of individuals that participate in the Forms, and in instantiating it also individuates. However, the Receptacle is unstable; it has a 'shaking motion' that prevents the Forms from being fully realized within it. The world of sense is thus at best a world of image, not of true reality, which resides only in the ideal world of Form. The matter receptacle is thus the source of the manifold defects of the world of sense, of the many ways in which it falls away from intelligibility and thus from the Good. The division between matter and mind is absolute.

In one crucial respect, Aristotle stood the system of his mentor, Plato, on its head. For him, change is not necessarily a falling away from intelligibility: it is the very means through which the intelligibility of the world around us is to be discerned. The paradigm for him was the living world, not the world of mathematical Form. He looked to behaviour – that is, change – to understand what a nature is, to what kind it belongs. Mathematical forms may be imperfectly realized by wooden triangles or copper squares, but living forms, in contrast, are ordinarily fully realized in the individual member of the species.

Aristotle began from the logic of change-sentences (McMullin, 1965). In contrast to Parmenides, who attempted to generate paradox by construing change as a movement from non-Being to Being, Aristotle saw such sentences as triadic: a subject (a leaf, say), a predicate (brown), and a lack, to begin with, of that predicate (non-brown). This allowed him to point out that the original lack cannot be regarded as non-Being; it conveys something real, namely the capacity or potentiality to become brown, a distinctive fact about the leaf. The 'matter' of the change is that which remains throughout – but it also, crucially, is the bearer of potentiality. Green leaves, though not brown, have the distinctive potentiality to turn brown at some point. This is something real about leaves, a potentiality that is crucial to our understanding of what leaves are. This important moral is one that may be drawn from every sentence that denotes a change.

The world for Aristotle was made up of substances, unities that exist in their own right as living things do. What if one of these ceases to be? What occurs is a change, not a replacement, so something must remain the same. The matter of such a change cannot have properties of any kind, he argued, for if it does, it must itself be a substance – which would mean that the change itself in that case would not be a truly substantial one. (This is his main objection to the various sorts of underlying 'stuff' postulated by his Ionian predecessors.) This led him to introduce first, or 'prime', matter, something that lacks all properties of its own and functions only to ensure the continuity, and hence the reality, of substantial change. Aristotle himself had little to say about prime matter, but his successors invested much effort in attempting to clarify this controversial notion.

What stands out in this story is that matter, as the one who introduced the term understood it, is not distinguished by any particular property. In the case of ordinary (non-substantial) change, the 'matter' ('second' matter, as it came to be called) is just the subject of the change, whatever its properties happen to be (a leaf, for instance). Where the change is substantial, the matter is necessarily property-less, not a constituent in the ordinary sense but something that came to be described as a metaphysical principle (McMullin, 1965, pp. 173–212). But whether it possesses formal properties or not, matter was seen by Aristotle first and foremost as the bearer of potentiality.

There were other features of the matter concept that came in for fuller treatment in the later medieval tradition. One was individuation (Bobik, 1965). Aristotle's substances had form and matter as co-principles or aspects, each requiring the other in order to constitute an existent thing. Form obviously could not individuate; it could be instantiated indefinitely many times. So individuation would have to come from the side of matter, and prime matter at that. But how? Prime matter was supposed to be indeterminate. Individuation clearly had something to do with location in space and time. After much discussion, it was decided that these properties belonging to the Aristotelian category of quantity would have to be part, at least, of the thing that designated something as an individual: '*materia signata quantitate*', as the phrase went. It was not at all clear that this new role attributed to matter was compatible with the earlier account of substantial change, although individuation clearly was involved in the ensuring of continuity of a body through such change.

What should be noted, however, is the introduction at this point of the notion of a 'quantity of matter' (Weisheipl, 1965). That would bear fruit in a different context – in the study, for example, of the phenomena of rarefaction and condensation, taken to be straightforward examples of substantial change of one element (water, say) into another ('air', or vapour). There are clearly quantitative constraints on such a change; the quantity of some 'stuff' otherwise indeterminate must be conserved. Richard Swineshead suggested, on intuitive grounds, that the quantity of this stuff, the quantity of matter, should be proportionate to the volume as well as to the density of the body concerned: the definition that Newton would later adopt as his own.

Parallel to this but in the very different context of motion, Jean Buridan postulated an 'impetus' in the case of moving bodies that is conserved in unimpeded motion and is a measure of resistance to change of motion. He too made it proportionate to the body's quantity of matter. The quantification of matter in this context was obviously a major step towards the mechanics of a later age. The issue of conservation had pointed Aristotle to the concept of matter in the first place, but now it was leading in a very different direction, one he had surely not anticipated.

One other development owed more to Plato than to Aristotle. From the beginning, Christian theologians favoured the strong dualism of body and soul that characterized the neo-Platonic tradition. This dualism was also described as being between 'matter' and 'spirit', thus leading to another rather different sense of the term matter – namely as a generic term that describes any item in the physical world. To be 'material' in this sense is simply to belong to the physical world, the contrast here also often described as being between the corruptible and the incorruptible. The operation of the human intellect was taken to be of a 'non-material' sort, incapable of being reduced to 'material' categories; indeed (as Aquinas and others held), ultimately independent of the operation of the brain. Defining mind in terms of the immaterial or the non-material would leave behind the issue of how the boundaries of 'material' action were to be drawn. No one at that earlier time could have guessed how difficult that would later become.

2.2 PHASE TWO: TRANSFORMATION

The seventeenth century marked a transformation in the concept of matter; one in which the burgeoning science of mechanics played the principal role. With the shift of focus from the world of living things to the more generic topic of bodies in motion came the rejection of the Aristotelian category of substance that had depended so much on the organism as paradigm. And with the disappearance of substantial form came the removal of the barrier to regarding change as involving 'stuff' with specific properties. In this reversal, Descartes played an important part (Blackwell, 1978). Convinced that the world should be fully intelligible to the human mind, and convinced further that the intelligibility of geometry furnished the model he needed, he equated the stuff of which the world was made – its 'matter' – with extension. Reducing the matter of bodies to their extension, a combination of their volume and their shape, would make the world fully amenable to the methods of geometry. The science of motion could then be rendered entirely mathematical, with the help of two intuitive principles: conservation of motion; and restriction of action between bodies to contact only.

However, there were some obvious barriers in the way of such a reductive picture of matter. First, the property of impenetrability would have to be smuggled in: extensions as such cannot collide! Second, and more serious, the lack of anything corresponding to density would make the construction of a plausible mechanics very difficult, if not impossible. Bodies of different densities obviously have different mechanical properties. Third, as matter and extension are the same, there is no empty space. How then are bodies to move? Descartes displayed extraordinary ingenuity in an effort to get around these and other difficulties, but it eventually became clear that a matter with only the single property of extension could not furnish the basis for an adequate mechanics.

The incentive for such a reduction remained, however, although now more realistically moderated to admit a handful of properties besides shape and volume: impenetrability, mobility, inertia, and perhaps density. There was a way of getting round admitting this last property: if one adopted the corpuscular model of matter, density could be explained in terms of degree of packing of corpuscles (assumed to be of uniform density) in an otherwise empty space. These properties were often defined as the 'primary' qualities of matter, in contrast to the 'secondary' ones. 'Primary' here could mean objective rather than subjective qualities, understanding the latter as dependent in one way or another on a perceiver. Or it could refer to the qualities in terms of which all others could be explained (McMullin, 1978a, pp. 32–38).

Either way, this commonly drawn distinction supported the 'mechanical philosophy' that came to dominate the work of seventeenth-century natural philosophers. According to these philosophers, matter was characterized by a small set of properties drawn from everyday experience. It was composed of tiny corpuscles, themselves invisible. The argument for a claim so sharply at odds with the growing empiricism of the day depended primarily at this point on a widely (although not universally) shared repugnance with regard to the consequences of allowing matter to be divisible into an infinite number of parts (Holden, 2006).

Corpuscular matter (so it was hoped) could in principle explain all the changes taking place in the visible world: for example, the chemical transformations described by Boyle in terms of underlying corpuscular structures and motions. As some saw (but others did not), validating explanations of this sort would require a new form of inference, one relying in the first instance on imagination for the invention of hypotheses about these underlying structures and requiring criteria for the assessment of a hypothesis more sensitive than a mere saving of the phenomena (McMullin, 1994). At this early stage such a programme was still largely promissory, of course. The unbounded faith in the corpuscular hypothesis was not matched by concrete results: one can point to scarcely a single successful explanation in corpuscular terms from that century.

The reductivist agenda of the mechanical philosophy fitted well with the growth, particularly in France, of what would come to be called 'materialism', that label recalling the neo-Platonic contrast between matter and spirit. In the writings of La Mettrie, d'Holbach, and their followers, materialism would take on a variety of forms, but it would always involve a denial of the existence of spirit, understood as something that lay outside the scope of the mechanical philosophy, and it would emphasize the reductivist claims of that philosophy. The 'matter' of the materialism of that day was made up in the first instance of the bodies of our ordinary experience, themselves believed to be composed of smaller bodies, like the larger ones in all respects save size. And the new mechanics would suffice (Newton postulated) for the small as it already had for the large.

Mentioning Newton recalls one further shift in the concept of matter, a shift for which he was responsible (McMullin, 1978b). He needed in his new mechanics a measure of a body's resistance to change in motion, as well as a body's gravitational effect on other bodies and its own capacity to be acted upon gravitationally. A fundamental postulate of his new mechanics was that a single quantity would be the measure of all three, plausibly, the amount of 'stuff' or the 'quantity of matter' (Buridan's term) of the body. For this, Newton introduced a convenient abbreviation, 'mass'. At that point, the older term 'matter' ceased to have any explicit function in the new mechanics, although it could still be said to remain implicitly present as the bearer of mass, whether inertial or gravitational. Matter could now be defined quite simply as that which possesses mass.

But what was one to make of the gravitational attraction at the heart of the new system? It clearly lay outside the bounds of the mechanical philosophy as it had been understood up to that time. It appeared to pose an unwelcome decision: either to treat it as action at a distance (generally regarded as unacceptable) or as mediated by something across intervening space. Newton himself had showed that this latter could not be a medium possessing inertial mass. But what other alternative was there? Over the years following the publication of the *Principia*, he tried out a variety of ideas, among them an 'elastic spirit' and an 'immaterial' medium (McMullin, 1978b, pp. 75–109). The reductivist concept of matter of the mechanical philosophers was clearly coming under strain at this point.[1]

Furthermore, matter itself seemed to occupy an ever-smaller part of Newton's universe. How were the particles of which light appeared to be composed able to traverse transparent media of considerable thickness? If they struck material corpuscles, they would surely be halted or at least diminished. Transparency could be explained only by postulating that the material corpuscles or atoms occupied merely a tiny part of the transparent body. And if this were so, might it not be the case in non-transparent bodies too? In the opinion of Samuel Clarke, Newton's disciple, the new mechanics entailed the view that matter is 'the most inconsiderable part' of the universe; the immaterial forces that in effect filled space were what really counted. Joseph Priestley would later write that according to the 'Newtonian philosophy' all the solid matter in the solar system 'might be contained within a nutshell' (Thackray, 1968).

Roger Boscovich carried this thought to its logical conclusion, dismissing solid extended matter entirely and replacing it with point-centres of force. Besides the long-range gravitational force of attraction, he postulated a short-range force of repulsion that would constitute something like an extended atom around each point-centre.

[1] Leibniz was an important contributor to this discussion; see Chapter 3 by Philip Clayton in this volume.

This 'atom' would not have a well-defined surface but the force of repulsion would make penetration more and more difficult, and in the end physically impossible, as the centre was approached.

Before this, potentiality had always been associated with an actuality of some sort. But Boscovich's atoms were not actual; they were themselves potential only, specifying what would happen if … If what? Could a potentiality trigger another potentiality? Clearly, a new sort of status was being attached to potentiality here, a kind of shadowy materiality. Others, like Kant in his early writings, would take up the challenge offered by this apparent paradox, noting that it at least avoided the more familiar paradoxes associated with infinite divisibility (Holden, 2006). However, the stubborn actuality of the world of ordinary experience made it difficult to countenance so radical a move.

And this sort of challenge would steadily strengthen as the eighteenth and nineteenth centuries progressed. Static electricity could apparently be stored. Ought it, therefore, to qualify as 'material'? The successes of the wave theory of light suggested an intervening medium of some sort … but what sort? Newton had shown that such a medium could not be inertial. But in that case, how could it be material? What was now to count as 'matter'?

It was from electromagnetic, not gravitational, theory that a resolution would ultimately emerge (McMullin, 2002). The successful portrayal of electromagnetism in field terms convinced Maxwell that the field had to be regarded as something more than a convenient calculational device. It had to designate a reality of a new sort, defined by the energy it carried, although understood as pure potentiality. In the earlier days of Newtonian mechanics, energy and momentum only gradually came to be recognized as significant quantities in their own right, mass retaining its dominant role. For a time, it was not clear which of the two, energy or momentum, would prove to have the all-important property of being conserved through change. Finally, that role was bestowed on energy. And with the advent of the field concept, energy did indeed appear to be emerging